Advanced Systems Lab Report

Autumn Semester 2017

Name: Simon Haefeli
Legi: 13-918-107

Grading

Section	**Points**
1	
2	
3	
4	
5	
6	
7	
Total	

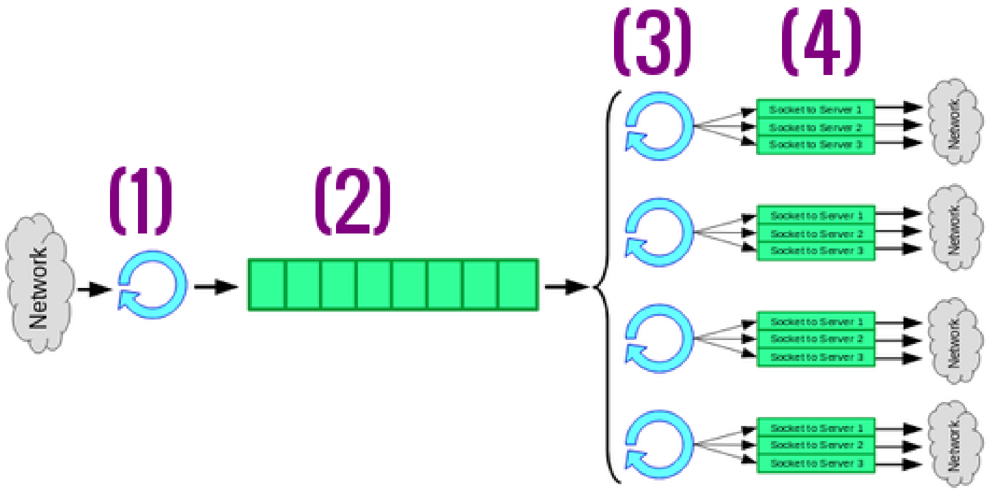
1 System Overview

1.1 Abstract

This project consisted of designing, implementing and evaluating the performance of a key-value store network system. We added a so called middleware between the memtier benchmark clients and the memcached servers that was able to forward the requests and answers and do some processing for certain particular requests. In this report, we are first discussing the way the middleware has been implemented, analyze results of different experiments and finally modelling our system.

1.2 General design and implementation particularities

Even though the general structure of the middleware was clearly defined, the components of the middlware asked for some important design choices. Here follow a small overview of the different implementation choices.



(1) The net thread is the thread that accepts connections from the clients, and reads the incoming requests to put them in the request queue (2). The *Java.nio* (non-blocking IO) package was used to achieve this purpose: A *ServerSocketChannel* was used as a welcome socket to accept connections from the clients by creating for each client a *SocketChannel*, and a *Selector* was used to iterate over the the sockets (the connection sockets and the welcome socket) to find entering requests for the middleware or connection requests. Using the *Java.nio* allows us not only to abstract the handling of a various number of connections, but also it iterates over the client connections in an optimal way by using *SelectionKeys*.

(2) The request queue is a java *LinkedBlockingQueue*, which has the useful properties to be unbounded and beeing FCFS. Requests wait in this queue until a worker thread is free.

(3) The request queue and the worker threads are both managed by the java *ThreadPoolExecutor*. The thread pool executor, which definition is:

```
ThreadPoolExecutor(int corePoolSize, int maximumPoolSize, long
    keepAliveTime, TimeUnit unit, LinkedBlockingQueue workQueue)
```

has a fixed number of worker threads by setting corePoolSize = maximumPoolSize. Putting a request into the queue or executing it, depending on the availability of the worker threads, is being done by the same following instruction:

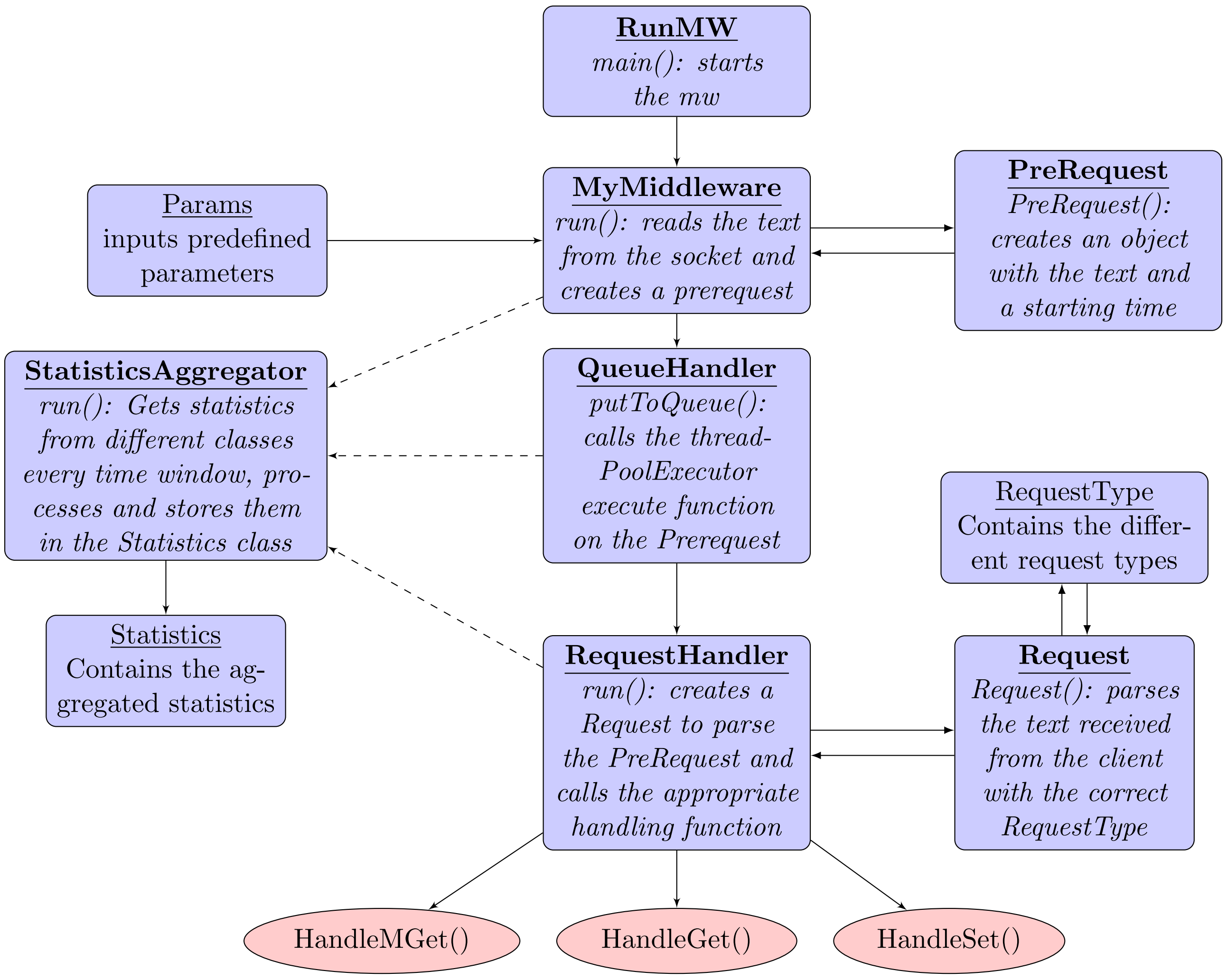
```
myThreadPoolExecutor.execute(Runnable command)
```

The *ThreadPoolExecutor* will execute the command if a worker thread is available, or put it to the unbounded queue if not, which is exactly the expected behaviour.[1]

(4) The connection sockets with the memcached servers are normal Java sockets, from the *Socket* class. Each worker thread opens a socket to each memcached server the first time it is beeing run and keeps it open until the middleware is stopped.

1.3 Request handling

We now want to look closer at the implementation of the middleware and how the pipeline looks like for a request being processed. The following flow chart illustrates this:


RunMW
main(): starts the mw
Params
inputs predefined parameters
MyMiddleware
run(): reads the text from the socket and creates a prerequest
PreRequest
PreRequest(): creates an object with the text and a starting time
StatisticsAggregator
run(): Gets statistics from different classes every time window, processes and stores them in the Statistics class
QueueHandler
putToQueue(): calls the threadPoolExecutor execute function on the Prerequest
RequestType
Contains the different request types
Statistics
Contains the aggregated statistics
RequestHandler
run(): creates a Request to parse the PreRequest and calls the appropriate handling function
Request
Request(): parses the text received from the client with the correct RequestType
HandleMGet()
HandleGet()
HandleSet()

[1]https://docs.oracle.com/javase/7/docs/api/java/util/concurrent/ThreadPoolExecutor.html, part on "Queuing"

To make some correpondencies with the general structure of the middleware presented in section 1.2, we see that the *MyMiddleware run()* function represents the net thread, the *Queue-Handler* class has a *ThreadPoolExecutor* field that manages the request queue and the call of the worker thread, and that the *RequestHandler run()* function represents one worker thread. We may also note that a PreRequest class is beeing created before putting the received message into the queue. This is to bind the message with a time, to be able to track the time a message spends in the queue.

At the end of the pipeline, the different requests are treated according to their type (get, set, or multi-get). In case of a set, the request is sent to all memcached servers sequentially, after what the worker thread waits for all the answers, also sequentially, as showed in the next line in the case of 3 memcached servers.

```
send to server 1
send to server 2
send to server 3
wait for answer 1 until received
wait for answer 2 until received
wait for answer 3 until received
merge the answers and send back to client
```

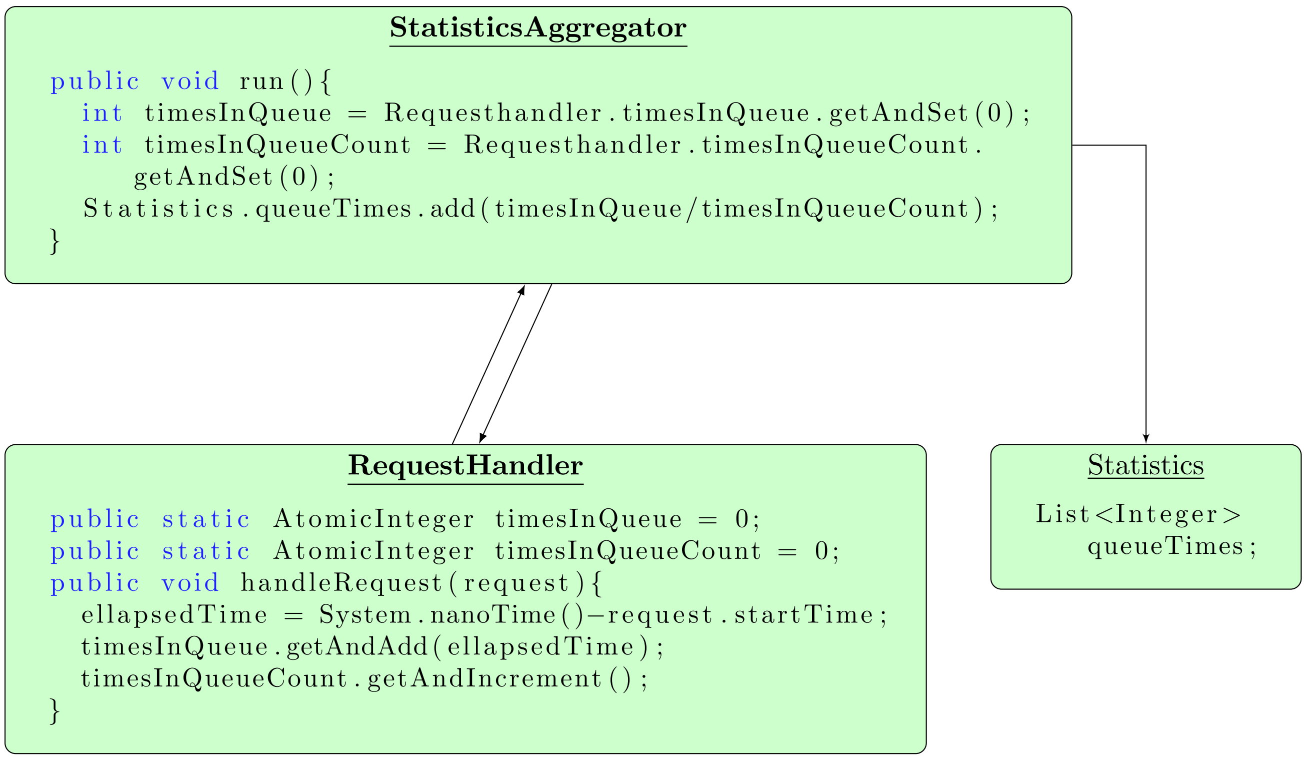
The main drawback of this design is that if one of the servers has a higher latency than the other ones, the worker thread might be waiting idle instead of starting to read the answers from the other servers.
In case of a get request, we simply forward the request to a given server. To decide to which memcached server we send the request, we simply keep a static field in the *RequestHandler* class which is shared accross the worker threads that keeps track of the last server to which we sent a get request. This variable is then beeing updated in a round-robin way.
In case of a multi-get, two cases are possible: In the non-sharded case, the request is simply being executed as a normal get. In the sharded case, the multi get is beeing splitted equally accross the different available memcached servers.

Finally, since we want the connections between the middleware and the servers to be open before running the experiments, we need to initialize these once for every worker thread. By defining the sockets in a *ThreadLocal* in the *RequestHandler* class, the initialization of the sockets will happen only the first time a worker thread is beeing called. That's why every thread is called once during the initialization phase of the middleware, by executing number of worker threads times the "init" requests, which are fake requests that don't need any special handling.[2]

1.4 Statistics gathering

Statistics have to be made in different classes accross the middleware, either a count (number of gets, number of sets,...), or an average (queue length, time in queue,...). These statistics are being stored in static atomic fields in the respective classes that can be gotten from the *StatisticsAggregator* class which is a *Runnable* called every second, the first time at initialization of the middleware. These statistics are then collected every given time window, averaged and stored in the *Statistics* class. This process is beeing illustrated in the next figure:

[2]According to the javadoc of the ThreadPoolExecutor class, "When a new task is submitted in method execute(java.lang.Runnable), and fewer than corePoolSize threads are running, a new thread is created to handle the request, even if other worker threads are idle". And that's why it is enough to run corePoolSize number of requests to have them run all once and thus initialized their sockets.



```
public void run(){
  int timesInQueue = Requesthandler.timesInQueue.getAndSet(0);
  int timesInQueueCount = Requesthandler.timesInQueueCount.
      getAndSet(0);
  Statistics.queueTimes.add(timesInQueue/timesInQueueCount);
}
```

```
public static AtomicInteger timesInQueue = 0;
public static AtomicInteger timesInQueueCount = 0;
public void handleRequest(request){
  ellapsedTime = System.nanoTime()-request.startTime;
  timesInQueue.getAndAdd(ellapsedTime);
  timesInQueueCount.getAndIncrement();
}
```

```
List<Integer>
    queueTimes;
```

The collected statistics in the *Statistics* class are then being filtered, by removing the warm-up time (according to some experiments I made, the middlware needs around 10 seconds to get stable data) and the cool down time (1 second), and removing the zero values that are present before and after the significative values (zeros that occur because of the late start of a memtier client for example or an early stop).
Finally, when the middleware is shut down, the average and standard deviation of every statistic is being computed and printed to a file. Depending on the experiment, we sometimes also print all the values to construct histograms.

2 Baseline without Middleware

The goal of this experiment is to study how the system would perform without the middleware. This part is important to get a better idea of what the performance limitations of the memcached servers and the memtier benchmark clients are, so we can better judge the impact of the middleware through the rest of the experiments.

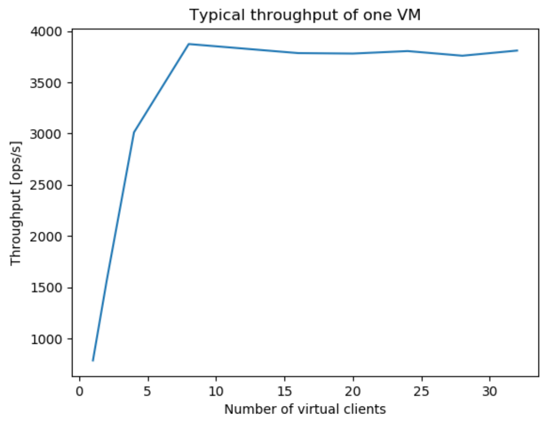
2.1 One Server

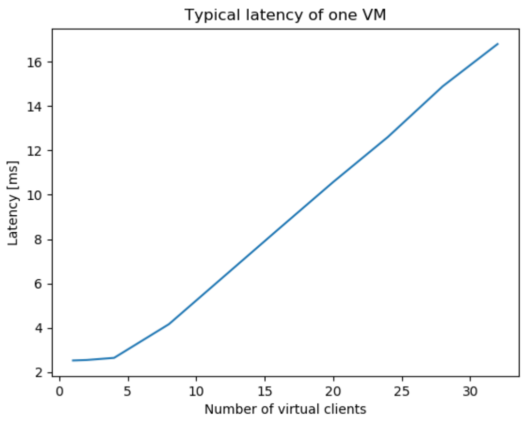
First, we want to analyze the performance evolution of the memcached server, and eventually find its upper-bound in terms of performance. To achieve this, we set up one single memcached server being queried by a various number of clients, for read-only and write-only workloads. More precisely, we are running experiments in the following configurations:

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..32]
Workload	Write-only and Read-only

2.1.1 Results and explanation

For a read only workload, we obtain the following plots for the latency and the throughput, for one client machine (the plots are very similar than the ones of the other client machines)[3]:





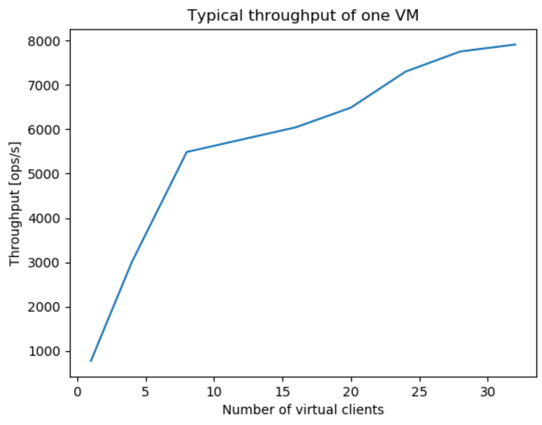
We notice that the maximum throughput is already obtained with 8 virtual clients per virtual machine and is then stable as we let the number of clients grow. This is, the memcached server starts to saturate when 3 VM with 2 threads and 8 virtual clients are querying a single server simultaneously. It is important to mention here that it is nearly impossible to over-saturate a server due to the way the memtier benchmark work: since we always run the clients with the default *–pipeline=1* argument, every CPM[4] will wait for an answer to come back before sending another request.
For the latency, we clearly see that it is inversely proportionnal to the throughput (we distinguish three different slopes on both graphs). In the phase when the number of virtual clients grows at a constant rate (number of virtual clients getting bigger than 8), the throughput also gets constant. The reason why the throughput doesn't drop but stays at approximately 4000 operations/second is because the higher latency is compensated by a higher number of virtual

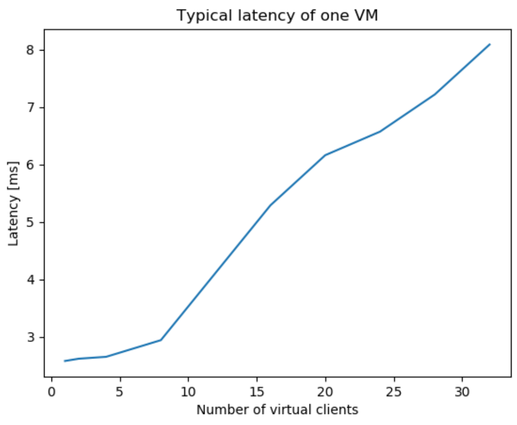
[3]To see which file has been used for which plot/table thoughout the report, please refer to the data.txt file
[4]virtual client per memtier, see project description

clients to keep the throughput constant. Also, as a sanity check, we can evaluate the interactive law. Knowing that the interactive law is :

$$requesttime(w) = \frac{numberofclients(N)}{throughput(X)}$$

that for example at 8 virtual clients with two threads in the memtier client, N = 16 and the throughput X is approximately 3800 ops/sec, it gives us a response time of 4.2ms, which perfectly corresponds. This sanity check also works with the resting results of this experiment. For a write-only workload, we obtain the following results:





For this workload, we note that we barely reach a saturated memcached server with 32 virtual clients, even if there is a clear drop in the growth of the throughput at 8 virtual clients. For write-only, the same observations apply as for the read-only workload.

However, we note a maximum throughput twice as high for sets than for gets, with a maximum latency twice as small. The different size of the messages being sent back and forth between the clients and the servers may not be the main factor, since for a get the messages are:

```
request: get memtier-9999,    answer: value memtier-9999 XXXXXX
```

and for the set they are:

```
request: set memtier-9999  0 10000 1024 XXXXX,   answer: STORED
```

which are quite the same length. This implies that memcached is either storing values faster than getting values, either send the *STORED* message back before starting the write operation, either having poorer performance than memtier benchmark when writting big messages to the connection sockets, or a combination of these factors. For this report, we will just keep in mind that the achieved throughput is higher with a write-only workload.

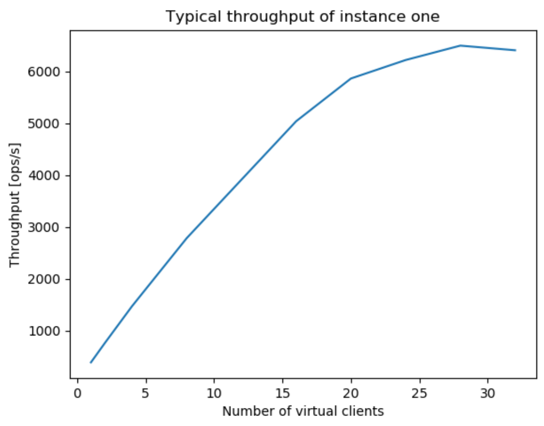
2.2 Two Servers

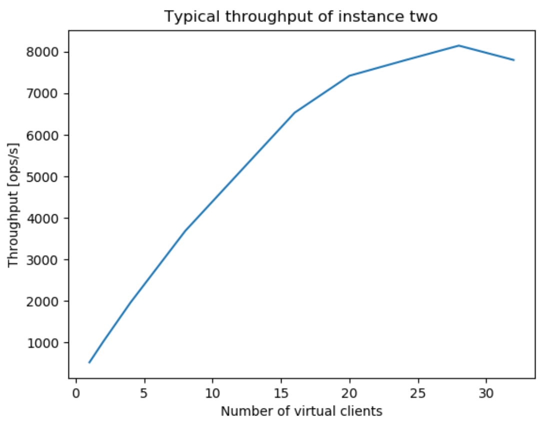
Now we are increasing the number of servers and putting a single client machine with a single thread to measure the performance limitations of the memtier clients with the following configurations:

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..32]
Workload	Write-only and Read-only

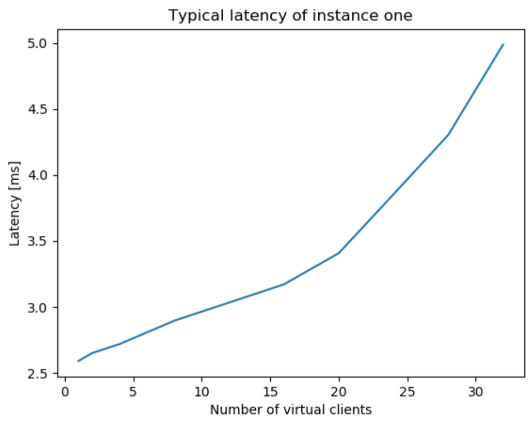
2.2.1 Results and explanation

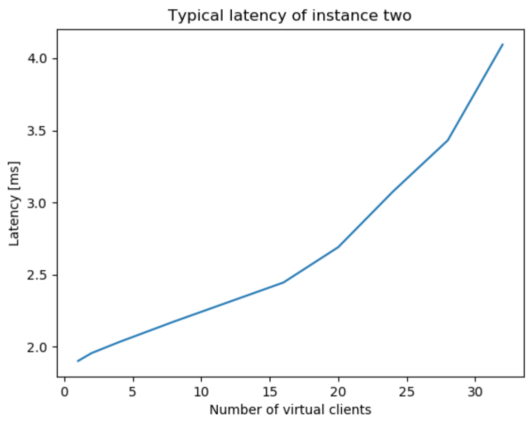
For a read-only workload, we obtain the following plots:



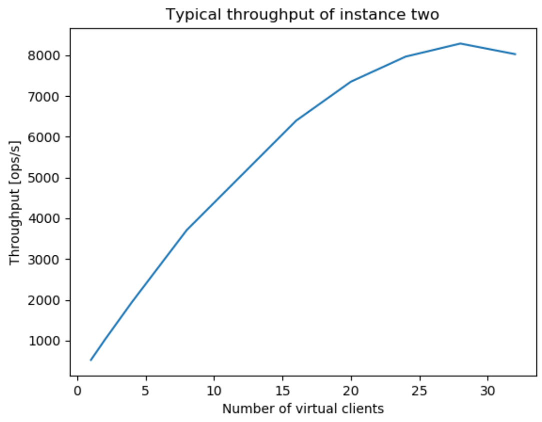


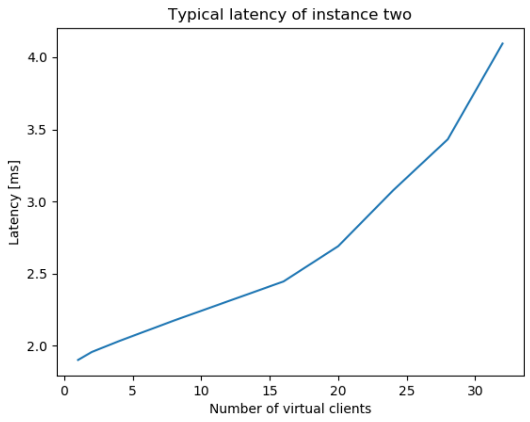
Remember that the client machine has two instances each connected to a different memcached server. It is important to notice at this point that the maximal throughput achieved by the two instances are not equal. As shown on the next figures, this is because the latency is higher for one of the two servers, which may be because of their geographic location (The server located further away from the client machine results in a higher latency).





For a write-only workload, we obtain for the server with higher throughput similar plots for throughput and latency than for a read-only workload:





We see that the system starts to saturate for the two workloads when reaching 28 virtual clients per thread, with a maximum throughput of around 8000 operations per second for the instance with higher throughput. We also note that contrary to the last experiment with a single server, the throughputs for write and read are similar. This proves for the last experiment that the memcached server saturates under a high workload, but tends to be more scalable for get-only operations. On the other hand, a single client machine cannot produce a higher throughput than 8000 operations per second, for read and for write.

2.3 Summary

Based on the experiments, we are now able to fill the table with the maximal throughputs for different configurations. To make the results suitable for comparison with the rest of the experiments, we sum up the throughputs observed on the different client machines. For the experiment with a single memtier client, we use the results of both instances to give a lower and upper bound (separated by a "/").

Maximum throughput measured on one VM

	Read-only workload	Write-only workload	Configuration gives max. throughput
One memcached server	11289	23836	8 VC for read-only, 32 VC for write-only
One load generating VM	6498/8146	6558/8287	28 VC

As explained in the previous sections, the key take-aways of this experiment are the following:

- The achieved throughput by the memtier clients and even instances may vary: because of the geographic positions of the clients or other factors.
- The memcached servers saturate faster for a read-only workload. For a write-only workload, the throughput can be twice as high and is limited by the performance of the memtier clients.
- The numbers of the first line in the table represent the maximum throughput a memcached server can achieve, as the second line represents the maximum workload a memtier client can achieve.

3 Baseline with Middleware

In this set of experiments we want to take a closer look at the effect of the middleware on the system. For this purpose, we are running experiments with different workloads, a different number of worker threads in the middleware, and one or two middlewares. This will show us in what way the middleware influences the results found during experiment two.

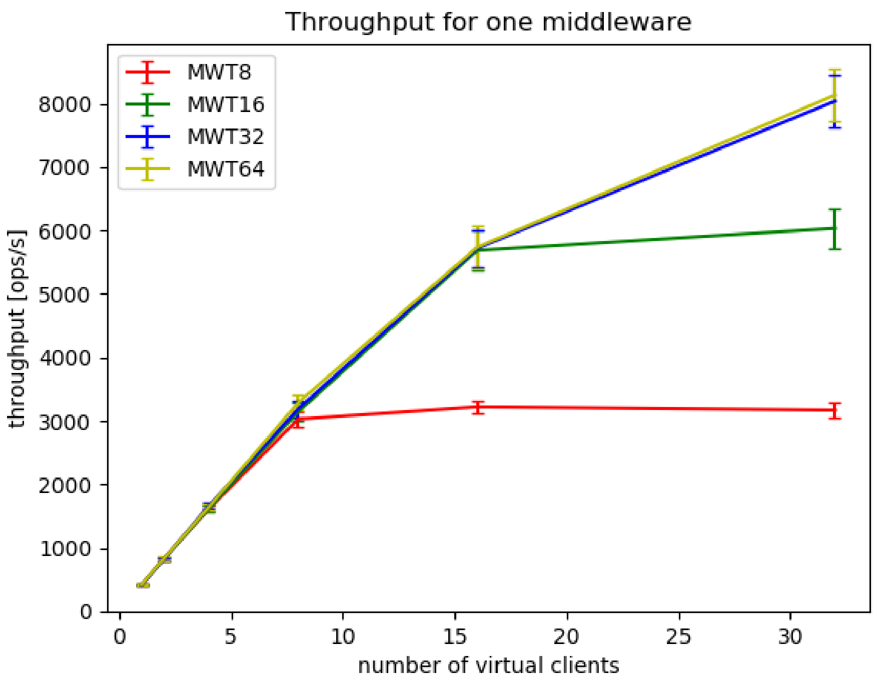
3.1 One Middleware

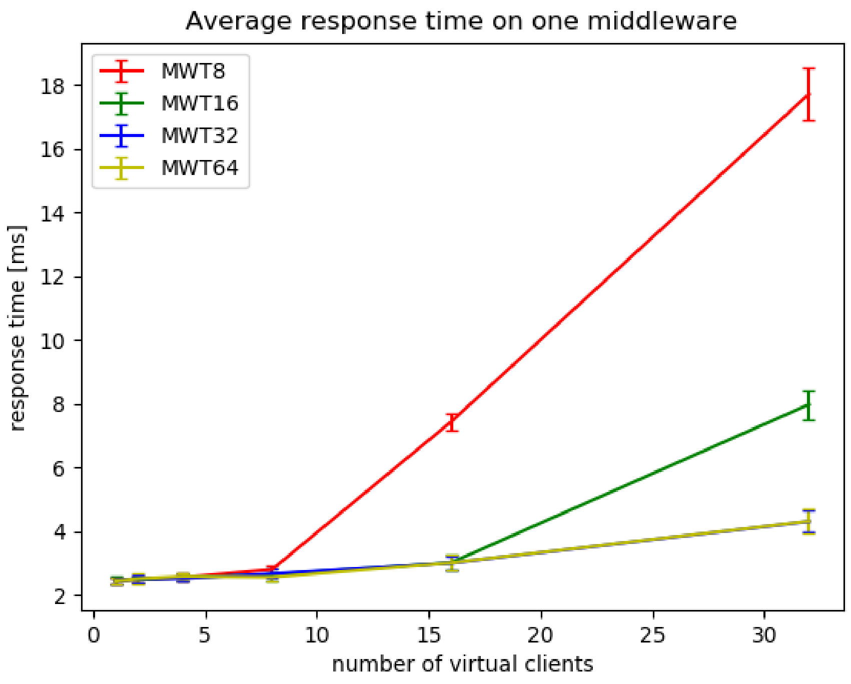
We start the experiment by connecting a single client machine to the middleware and one memcached server, for different workloads and number of worker threads:

Number of servers	1
Number of client machines	1
Instances of memtier per machine	1
Threads per memtier instance	2
Virtual clients per thread	[1..32]
Workload	Write-only and Read-only
Number of middlewares	1
Worker threads per middleware	[8..64]

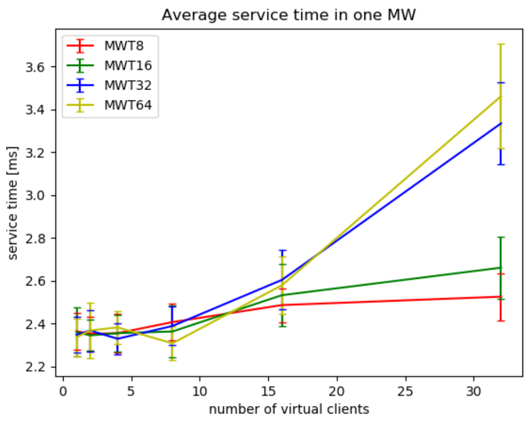
3.1.1 Results and explanation

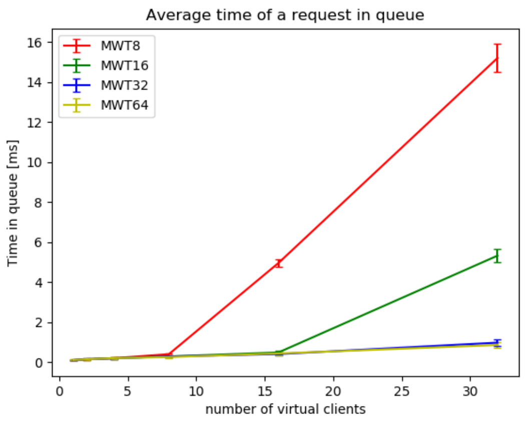
The throughput and the response time for a read-only workload measured on the middleware give the following plots (the plots for write-only are the same):





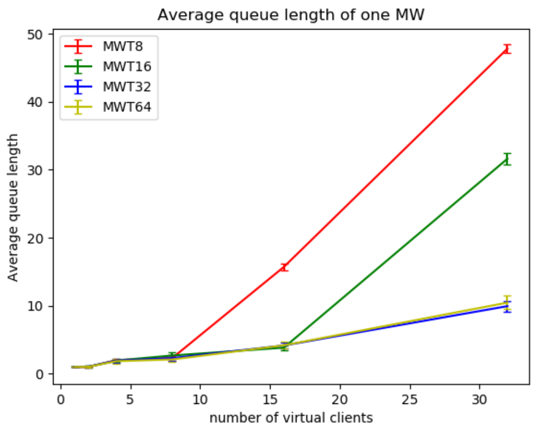
Note that the response time mesured is the addition of the service time and the waiting time in the queue, as showed by the two following plots.



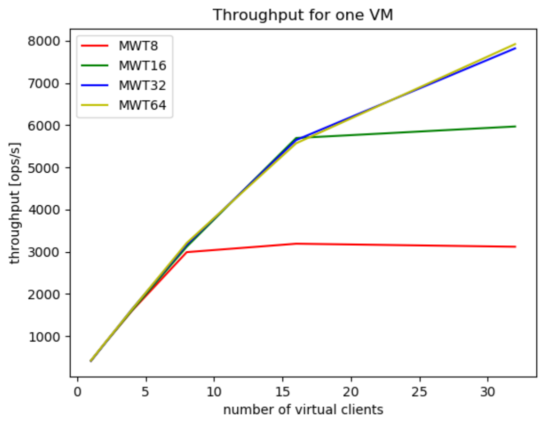


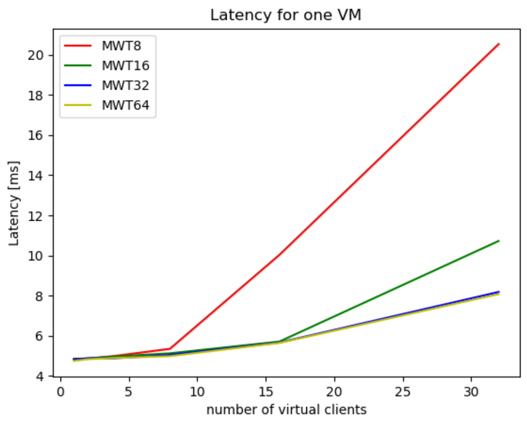
The service time of the middleware is extremely close to the time it takes to send and receive an answer from the memcached server (the difference can be neglected). Since the parsing times are very small compared to the answer time of memcached, the answer time and the service time are nearly equal.
The interactive law is also respected for the configurations where the maximum throughput is achieved. If we take for example 16 middleware worker threads and 32 virtual clients, we obtain N = 64, X = 6000, and thus w = 10 ms, which is not far from what we ploted (in reality, as we will see later, the time spent in the middleware, known as "think time" has also to be taken into account).
From the four of these plots, we see that the middleware is the bottleneck for a configuration with 8 and 16 middleware worker threads, since the throughput stays constant after respectively 8 and 16 virtual client and, as seen in the last experiment, the maximum throughput that can be achieved by memtier is higher than the throughputs achieved here. More precisely, the bottleneck in the middleware is the time a request spends in the queue, as shown by the

strongly growing curve of the average time in queue for 8 worker threads for example. This strong growth is also correlated to the average queue length: as shown in the next figure, the queue length is growing with the time a request spends in queue, since the middleware has not enough threads available to execute the requests.



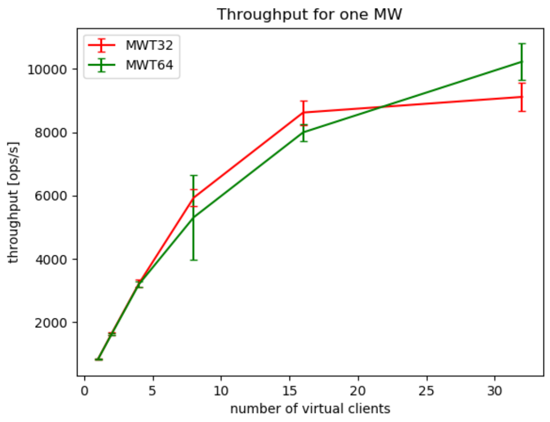
As a sanity check, we also plot the latency and the throughput observed on the client:

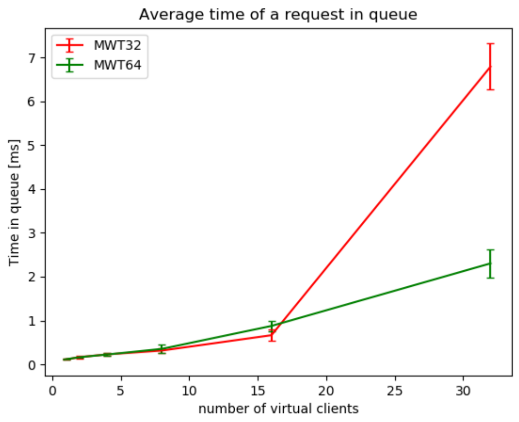




There are two interesting points to notice: first, the throughput measured on the middleware is equal to the one measured on the memtier VM, which is due to the way memtier works. As explained in section 1, one memtier CPM doesn't send a new request until the last one has not been received. Secondly, the graph of the latency is similar as the one for the response time on the middleware, but shifted by 2ms on the y-axis, which is due to the travelling time between the middleware and the memtier client.

As a last point, because we haven't reached a saturated middleware with 32 and 64 worker threads, we re-run the experiment with an increased number of generating client VM number (2), to obtain the following results:





We note that by increasing the workload, we are able to saturate the middleware with 32 worker threads, again, due to a slope change in the queuing time. For 64 worker threads, we are tending to reach a saturated state at around 11000 operations per second, which also corresponds to the maximum throughput a memcached server can achieve with a read-only workload. To make sure that the middleware becomes the bottleneck under high workload even with 64 worker threads, we have run all this experiment with a write-only workload also, and obtain for every configuration and every statistics the same plots. Seen that the maximum throughput of the memcached server under a write-only workload was around 20000 ops/second, we can conclude that the middleware will start to become the bottleneck under any configuration if the throughput is high enough.

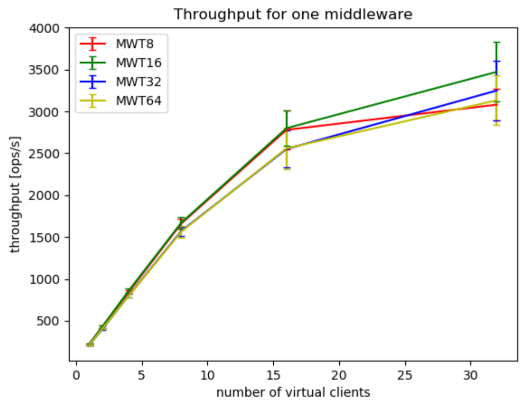
3.2 Two Middlewares

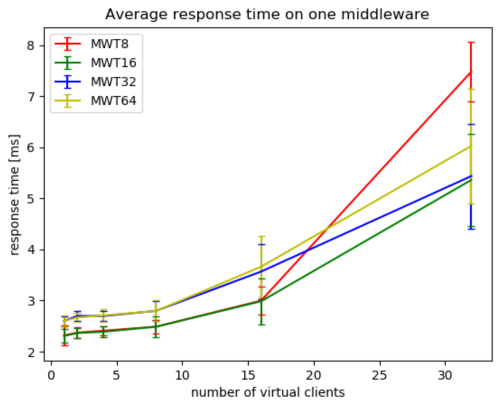
We continue the experiment by connecting one client VM with two instances of memtier to two different middlewares VMs and one memcached server:

Number of servers	1
Number of client machines	1
Instances of memtier per machine	2
Threads per memtier instance	1
Virtual clients per thread	[1..32]
Workload	Write-only and Read-only
Number of middlewares	2
Worker threads per middleware	[8..64]

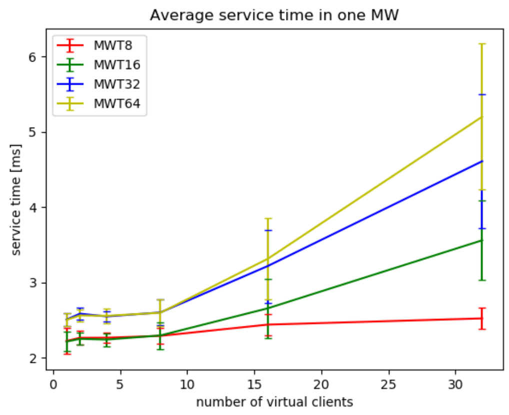
3.2.1 Results and explanation

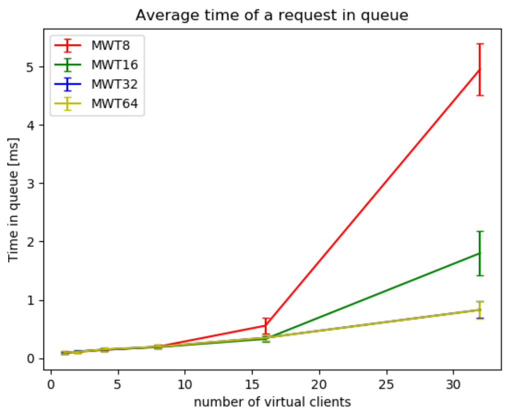
We obtain the following plots for the throughput and response time measured on one middleware with similar plots for read-only and write-only workloads:





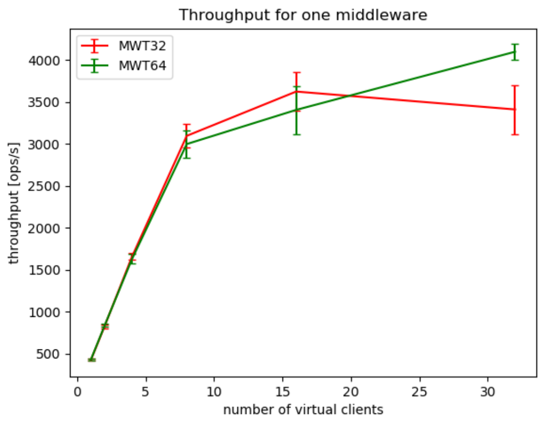
We directly notice that the difference of throughput and reponse time between different numbers of worker threads configuration isn't as significant as during the last experiment. As we will see on the next plots, this is because the high queuing time for a lower number of worker threads is compensated by a low service time and inversely.

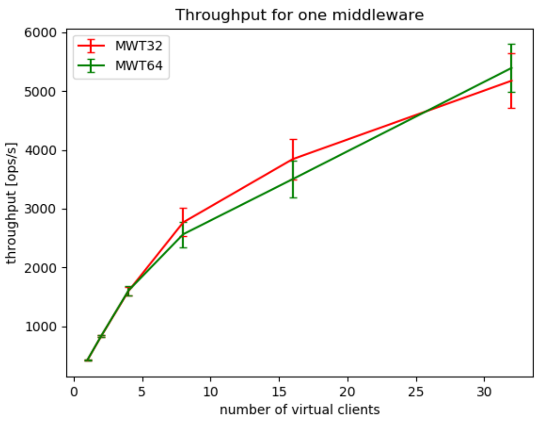




We should also take into consideration that the workload exerced on one middleware is halved compared to the last experiment , where there was only one thread per memtier instance and not two, which explains why the average time in queue for 8 worker threads only starts to grow faster after 16 virtual clients as opposed to 8. Furthermore, the throughput at saturation for 8 middleware threads is equal to the last experiment. Deducing from the previous experiment where we learnt that the bottleneck in the middleware is the queuing time, and the graphs above, the middleware hasn't reached its maximal throughput for the other configurations.

However, when we double the load on the middlewares, we can see that our middleware isn't the bottleneck of the experiment if we put a high number of worker thread, but the memcached server. If we remember the conclusions from the baseline without middleware, the read-only achieves a smaller maximal throughput than the write-only, and that's why we can suddenly see a big difference in terms of throughput between the two workloads, since we showed during the last experiment that the middleware achieves the same performance for the two workloads when it is the bottleneck. This is shown by the following two graphs, the left one being a read-only workload and the right one a write-only workload (rep 2 mw1 used).





To confirm our claim, the calculation of the total throughput of the two middlewares on the single memcached server for a read and write only are (the two middlewares don't have the same throughput, but their statistics have exactly the same shape):
read : 4173+7043 = 11216 operations/second

write : 5452+10753 = 16205 operations/second
Hence, because the maximum throughput of a single memcached server for read-only workload was 11289, and 23836 for write-only, this proves that the memcached server is the bottleneck for this further experiment. This is, we can reach the memcached server upper-bound with a configuration with 64 worker thread and 2 connected middlewares.

3.3 Summary

The maximum throughputs for different configurations are summarized in the following table. The throughputs are beeing added over all the VM as well for the middlewares than the clients.

Maximum throughput for one middleware.

	Throughput	Response time[ms]	Average time in queue[ms]	Miss rate
Reads: Measured on middleware	10638	6.69	2.07	14%
Reads: Measured on clients	10266	12.25	-	14%
Writes: Measured on middleware	10477	7.17	2.13	-
Writes: Measured on clients	10128	12.63	-	-

For this experiment, we take the average of the times since both middlewares don't have the same throughput.

Maximum throughput for two middlewares.

	Throughput	Response time	Average time in queue	Miss rate
Reads: Measured on middleware	11216	10.21	1.09	0.1%
Reads: Measured on clients	11618	12.246	-	0.1%
Writes: Measured on middleware	16205	6.305	0.93	-
Writes: Measured on clients	16019	8.915	-	-

As explained in the previous sections, the key take-aways for this experiment are the following:

- The bottleneck of the middleware is the queuing time of the requests. When the number of worker threads is too low, this value tends to grow very fast.
- The same observation applies for a configuration with two middlewares. If the performance of the memcached servers and memtier benchmark clients were infinitely good, we would expect a performance twice as high than for one middleware, since they are running independently. But this is not the case and could show that we can achieve the upper-bound of the memcached server with two middlewares.

4 Throughput for Writes

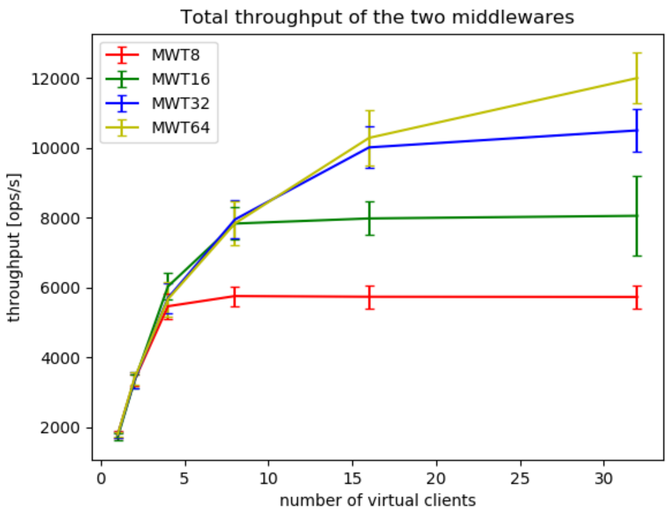
4.1 Full System

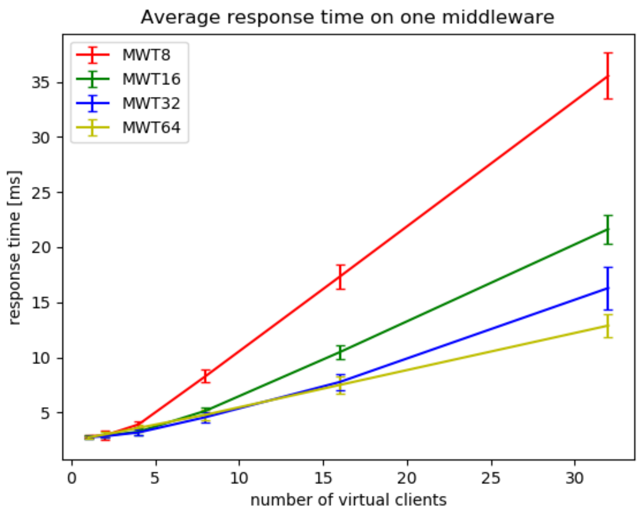
The purpose of this section is to assess the behaviour of the middleware with a write-only workload and increased number of clients and servers.

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..32]
Workload	Write-only
Number of middlewares	2
Worker threads per middleware	[8..64]

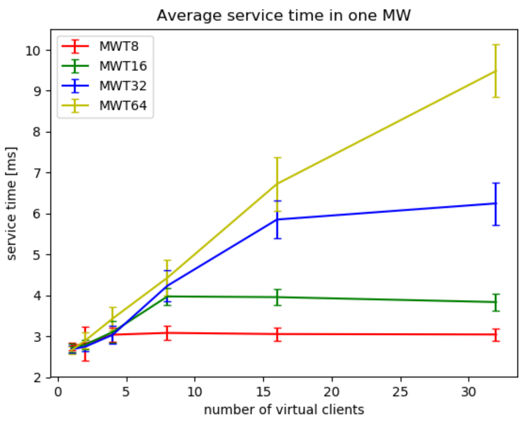
4.1.1 Results and explanation

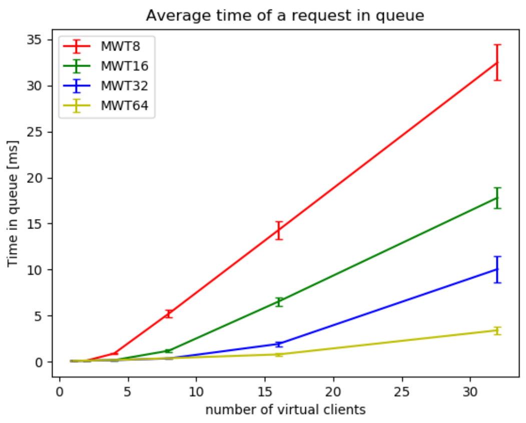
The statistics of a single middleware have as expected the same shape than during last experiment, and are nearly equal between two middlewares. Hence, we plot here the total throughput of the two middlewares and the other statistics from one single middleware.



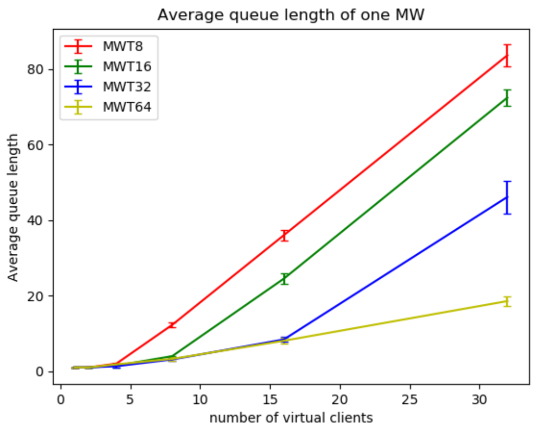


The interactive law also holds for this case. If we take for example 32 worker threads at 16 virtual clients, we get N = 16*6 (since there are 3 clients putting workloads on these two middleware), X = 10000, we get w = 0.0096 = 9.6 ms, which is approximately correct. We further notice that the latency takes much higher values than during the last experiment, which is due to an increased workload from more clients.
We now want to get an insight on the service time compared to the queuing time.





We notcie that the service time stays constant after reaching a certain threshold. As we can see on the graph on the right, this is because of the time a request spends in queue. At one point, too many requests enter the middleware and can't be processed directly due to the number of available worker threads. We also see that the service time is higher for an increased number of middleware threads, which is due to the workload being put on the memcached server. For a low number of worker threads, the service time stays low due to an under-saturated memcached server. A tradeoff between service time and average queuing is also to be seen: A higher number of worker threads will increase the load on the memcached server and increase its response time, whereas a too low number of middleware threads skyrockets the queuing time. This is why the gap between the response times (single graph above for response) is big for a low number of middleware threads and grows smaller when increasing the number of worker threads.
At last, we have a look at the average queue length in the middleware:



As said in the previous experiment, the average queue length follows the shape of the queuing time. A small calulation allows us to explain these numbers. If we consider our middleware with m number of worker threads, an average queue length of L, the service time being s, and the waiting time in queue beeing T, we can verify that:

$$T = \frac{L}{m} \cdot s$$

which is just the number of requests awaiting for a given worker thread times the average service time of one worker thread. For example, if we take m = 16 and the number of virtual clients 32, we have L = 65, s = 4ms, and thus we obtain T = 16.25ms, which corresponds to what we measured.

4.2 Summary

To fill in the summary table, we do the total throughput of the middlewares, and take one representative statistics for the rest. For the throughput derived from the MW response time we use the interactive law as showed at the start of this section.

Maximum throughput for the full system

	WT=8	WT=16	WT=32	WT=64
Throughput (Middleware)	5734	8060	10507	12008
Throughput (Derived from MW response time)	5485	9142	12000	14906
Throughput (Client)	5769	8438	10384	11791
Average time in queue[ms]	31.2	18.3	10.0	3.4
Average length of queue	84	72	47	19
Average time waiting for memcached[ms]	2.9	3.9	6.1	9.3

The key take-aways for this experiment are the following:

- There exists a tradeoff between the queuing time and the time waiting for memcached: The higher the number of worker threads, the higher the load on the memcached servers, but the lower the queuing time becomes and inversely
- We could apply a simple law that links the service time, the number of worker threads, the length of the queue and the queuing time, as well as the interactive law.

5 Gets and Multi-gets

In this set of experiments we will have a closer look at the behaviour of the system with get and multi-get requests. First, the sharded case, where the middleware splits the requests among the servers, and secondly the non-sharded case, where the request is handled as a normal get.

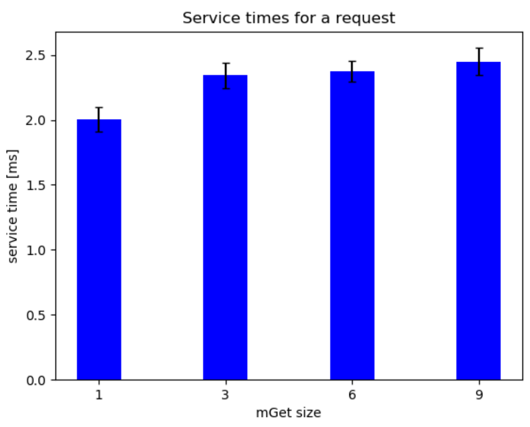
5.1 Sharded Case

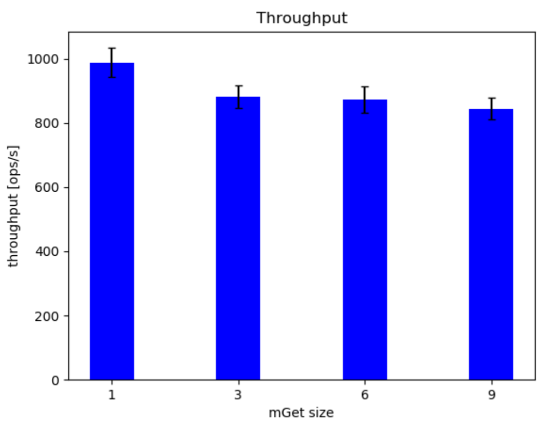
The memtier workload is adapted so that memtier sends one set alternated with one multi get of the key-size we want. Also, we use 64 middleware threads to achieve maximum throughput.

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	[1:1, 1:3, 1:6, 1:9]
Multi-Get behavior	Sharded
Multi-Get size	[1, 3, 6, 9]
Number of middlewares	2
Worker threads per middleware	64

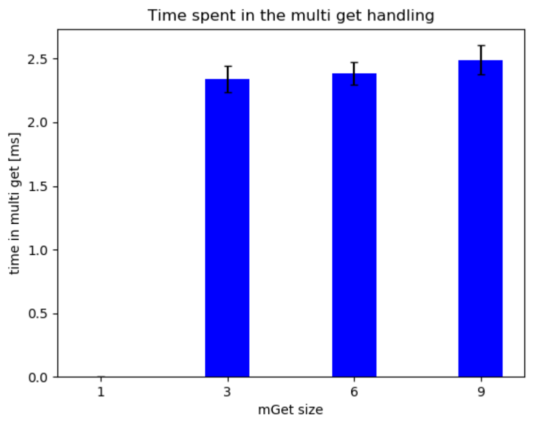
5.1.1 Results and explanations

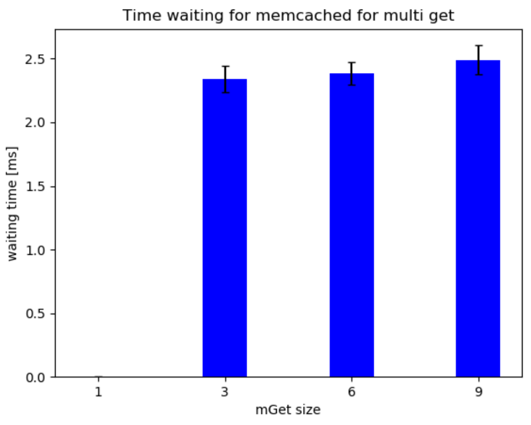
First, we analyze a couple of statistics on the middleware to understand its behaviour. The throughput and the service time in the middleware are plotted:



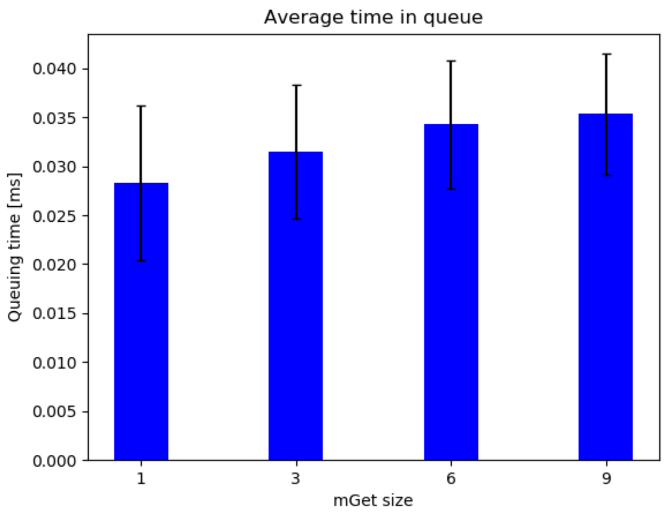


We observe that the service time increases with the key size, which is normal since the processing the middleware has to do for different key sizes is approximately equivalent, but the time taken by the server to process the request and sending the packet back is higher for a bigger key amount. For the sharded case, we know that the middleware has to split the requests into different servers, which may cause a bigger processing time. However, this additional processing time can be neglected as shown by the following graphics (the left one represents the total time a request spends in the multi get handling, whereas the right graphic shows the waiting time for memcached in the multi get handling). In fact the differences between the two is in micro seconds.

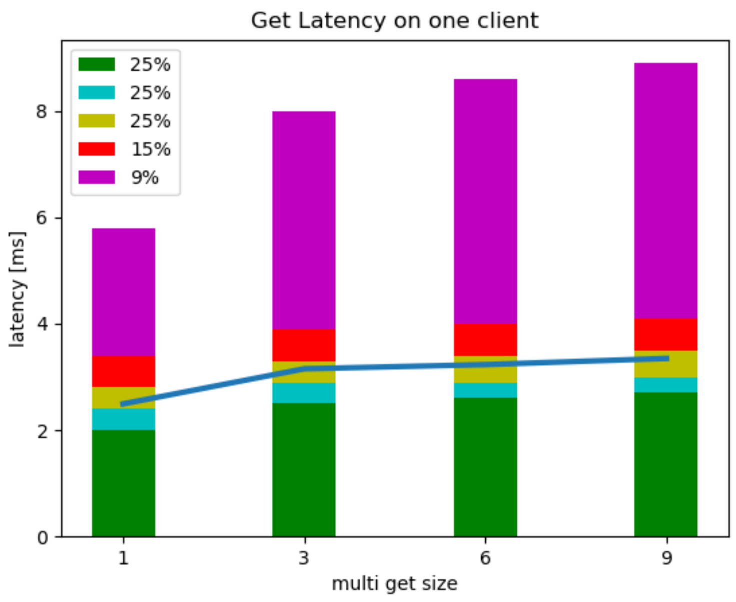




Two comments have to be made regarding these graphs: first, we see that there is no statistic for a key size of 1, this is because a multi get with size one is handled as a get in the middleware and thus isn't part of the multi get statistics. Secondly, we observe that the time spent in the multi get handling is equivalent to the service time. This is because the parsing time of a request is still very small even if the size of the message grows.
In the previous sections, we discovered that the time spent in the queue was the bottleneck of our system. However, in a multi get configuration, this isn't the case any more as shown by the following figure, which plots the time spent in queue:



On the client side, a closer look is taken to the latency distribution of the requests. The plotted line represents the average latency. The colors represent the percentage of the requests that are in a certain latency range. Thus, the top ends of the color bars represent respectively the 25th, 50th, 75th, 90th and 99th percentiles.



We observe a similar behaviour than on the middleware with a small growth of the latency and that the values are clustered around the average as expected. A closer look at the distribution of the latency will be made at the end of this section.

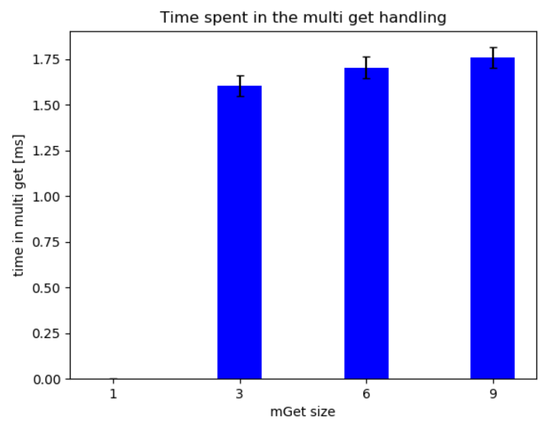
5.2 Non-sharded Case

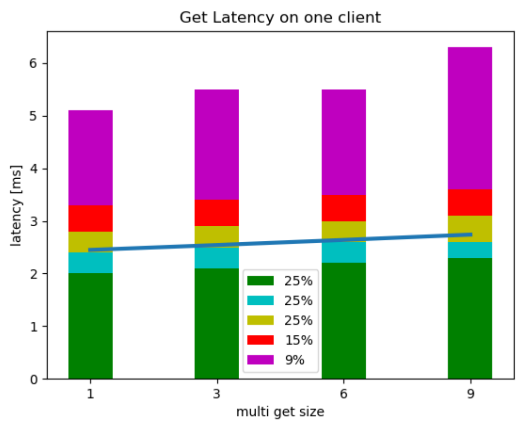
The middleware is now being run in non-sharded mode. A multi-get request is therefore handled in the same way as a normal get.

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	[1:1, 1:3, 1:6, 1:9]
Multi-Get behavior	Non-Sharded
Multi-Get size	[1..9]
Number of middlewares	2
Worker threads per middleware	64

5.2.1 Results and explanation

The results are extremely similar to the sharded case: we observe a growth of the latency with number of keys in the multi get. The latency as observed on the middleware and on the clients are shown as followed:

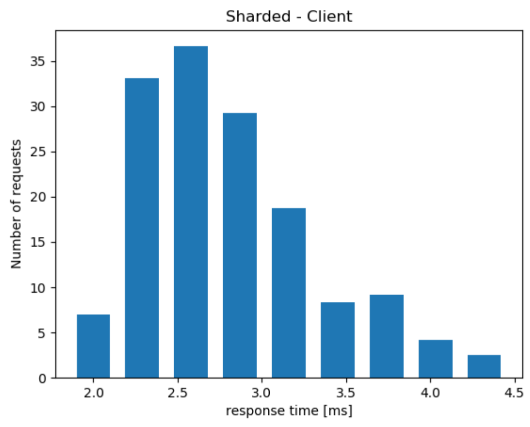


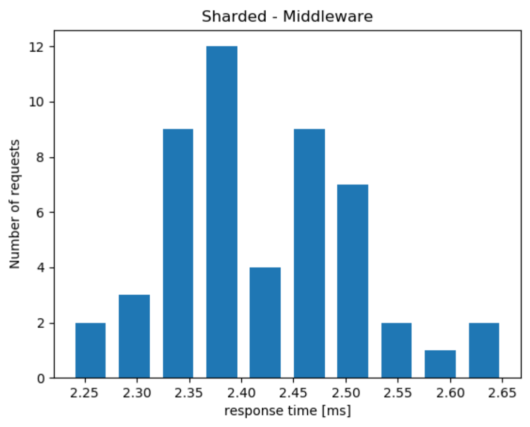


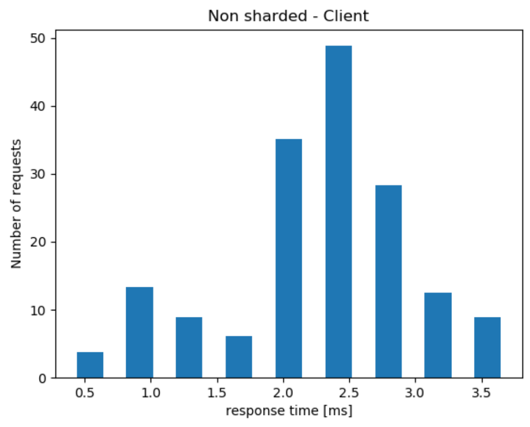
For this part, there is no surprise regarding the obtained results. As the key size grows, the memcached server needs more time to process the request and send the answer back, and thus we observe a growth of the latency. A detailed comparison between the sharded and non sharded case can be found under the two next sections.

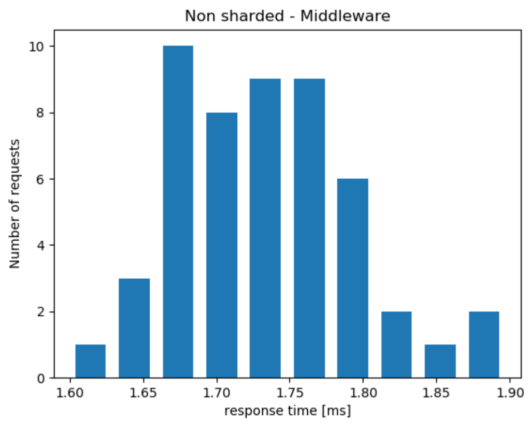
5.3 Histogram

The distribution of the latency as measured on the middleware and the client, for both sharded and non sharded case, for a key size of 6, gives the following plots (the histograms are constructed in a way so that bins having less than one request are not displayed):









5.4 Summary

All the histograms seem to follow a gaussian distribution around a shifted mean. First, we notice that measured on the client is slightly higher than the one measured on the middleware, due to the travelling time between the middleware and the client. Secondly, more interesting, the latency is on average higher in the sharded case than in the non sharded case.
This can be explained by the followings:

- The server performance is similar if it receives 2 keys in the get requests (in the sharded case with 3 servers) or 6 keys. This claim can be proved by looking at the graph in section 5.2, where we see that the difference of time spent in the multi get handling between 3 and 6 keys , i.e the waiting time for the memcached server, is very small. Hence, reducing the key size from 6 to 2 isn't enough to observe a significant difference in latency. With a multi get key size of 9, the difference wouldn't have been significant either, by refering to the same graph again, since the request would have been split in sizes of 3. A major difference could have been observed if we had a key size of n which overwhelms the server, whereas a size of n/3 doesn't. However, n=9 isn't enough to overwhelm the server, even with a very low miss ratio (1%)
- The way the middleware handles a multi-get request in the sharded mode isn't optimal. The pattern followed by the multi get handling is the same as the one for a set request, namely:

```
1       prepare the splitted requests
2       send to server 1
3       send to server 2
4       send to server 3
5       wait for answer 1 until received
6       wait for answer 2 until received
7       wait for answer 3 until received
8       merge the answers and send back to client
```

  Like we discussed in the previous section, the point 1 is extremely efficient and can be neglected. However, waiting sequentially for an answer from a server can be bad if the response times are different as explained for set request.

6 2K Analysis

In this section we perform a 2k analysis with 3 parameters and 3 repetitions. We want to analyze the explained variation of the number of servers, the number of worker threads and the number of middlewares.

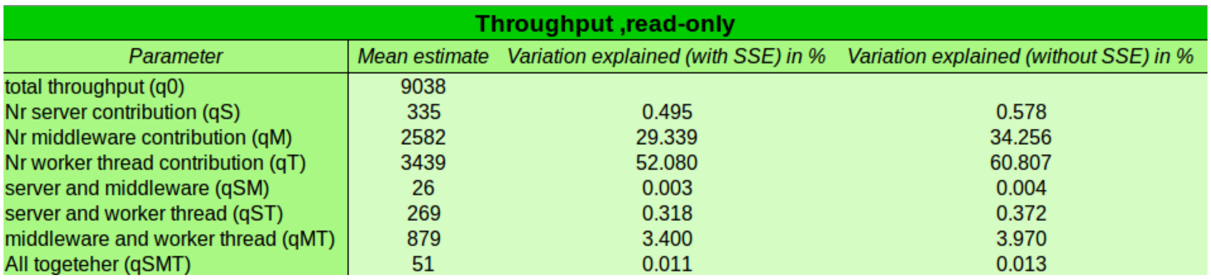
6.1 Parameters of the experiment

The following configuration are beeing experimented:

Number of servers	2 and 3
Number of client machines	3
Instances of memtier per machine	2
Threads per memtier instance	1
Virtual clients per thread	32
Workload	Write-only, Read-only, and 50-50-read-write
Number of middlewares	1 and 2
Worker threads per middleware	8 and 32

6.2 Results and explanation

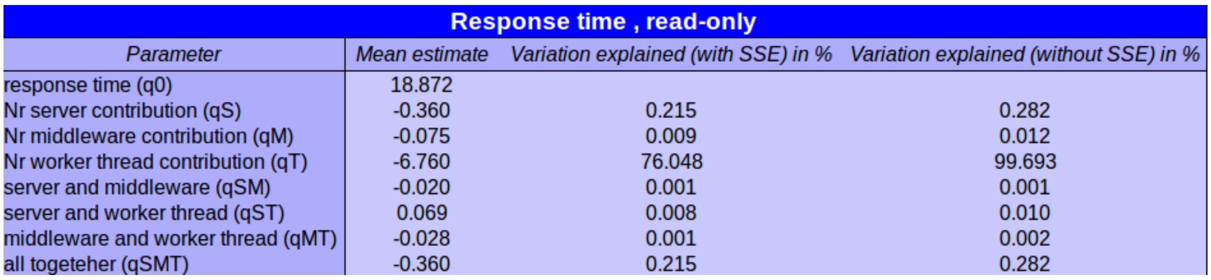
The full calculations for this 2^3*3 analysis can be found in the excel sheet called *SummaryStats.ods*. The final results obtained for a 2k analysis for the throughput are displayed here:



Throughput ,read-only			
Parameter	*Mean estimate*	*Variation explained (with SSE) in %*	*Variation explained (without SSE) in %*
total throughput (q0)	9038		
Nr server contribution (qS)	335	0.495	0.578
Nr middleware contribution (qM)	2582	29.339	34.256
Nr worker thread contribution (qT)	3439	52.080	60.807
server and middleware (qSM)	26	0.003	0.004
server and worker thread (qST)	269	0.318	0.372
middleware and worker thread (qMT)	879	3.400	3.970
All togeteher (qSMT)	51	0.011	0.013

The obtained results are as expected, not a surprise.
For the throughput, the contribution of the variation of the number of servers is very low. As it could be seen during the last experiments, the time spent in queue in the middleware has always been the bottleneck of our system when using a single get workload. In addition, as observed in experiment 5, using more servers doesn't improve the total time waiting for the memcached server(s), and thus, changing the number of servers only explains few variation.
The explained variation is basically shared between the the single contribution of the increase of the number of middlewares, and the single contribution of the increase of the numer of worker threads. This point has also been highlighted in the previous experiments: The throughput increases drastically with the number of worker threads, and increases up to a certain point with two middlewares because of the memcached server capacity and that's why the variation explained by the middleware is twice as high than the variation explained by the number of worker threads. This is the last proof that the times in queue is the biggest bottleneck in our system, and that changing its value influences a lot on the throughput.
We finally note that the different factors of this experiment are quite independent since their combined values are very low.

For the response time, the 2k analysis leads to the following results:



Response time , read-only			
Parameter	Mean estimate	Variation explained (with SSE) in %	Variation explained (without SSE) in %
response time (q0)	18.872		
Nr server contribution (qS)	-0.360	0.215	0.282
Nr middleware contribution (qM)	-0.075	0.009	0.012
Nr worker thread contribution (qT)	-6.760	76.048	99.693
server and middleware (qSM)	-0.020	0.001	0.001
server and worker thread (qST)	0.069	0.008	0.010
middleware and worker thread (qMT)	-0.028	0.001	0.002
all togeteher (qSMT)	-0.360	0.215	0.282

For the response time, we note that the contributions are all negative. This is, because of the fact that if we increase a factor (for example from 8 worker threads to 32), we decrease the response time.
For the reponse time, only the variation of the number of middleware threads has an influence on the response time. The number of servers has (nearly) no influence on the response time, for the same reason that it didn't have for the throughput. On the other hand, the number of middleware has also no influence on the response time, because the response time on two middlewares are independent of each other as long as the memcached servers (which are the same for the two middlewares) are not saturated, which is not the case as we can observe in this table. In the case where the servers would be oversaturated, we would have a positive contribution for qM. Finally, the number of worker threads is again the main contributor to the variation of response time. For the same reasons as for the troughput, a higher number of worker threads leads to a lower queuing time and thus a faster response time.

The response time and the throughput tables for the other workloads are very similar and are not treated in this report (but can be found in the *SummaryStats.ods* file), since the same comments apply to them.

7 Queuing Model

So far, statistics have been collected, plotted and analyzed. We now want to model our system to be able to predict these different statistics. The statistics that we calculate and compare with the statistics collected on a single middleware are taken from the book *The Art of computer systems performance analysis by Raj Jain*, pages 532 and 536.

7.1 M/M/1

To model our system as a M/M/1 model, the statistics collected from experiment 4 are used. The M/M/1 model is a basic modelling system that models one queue with exponentially distributed service times and arrival rate (the two "M"), and one "server". In our case, this means that the M/M/1 model represents a system where the requests arrive on one unique queue and are being processed by a "single-processor" system, i.e one unique thread that takes and processes the requests from the queue.
To be able to model our system as a M/M/1 model, we need to tweak the results somehow to make it appropriate to be used to calculate the statistics. In our middleware, we computed the mean service time that a worker thread takes to process a request, which is (as can be seen in the stat files) representative of the service time of a single worker thread. Assuming that this mean service time is the service time of the "single-processor" is incorrect: it leads to assume that one request is being handled during the average service time of a worker thread. In fact, if the number of worker threads on the middleware is *mwt*, approximately mwt requests are being handled during this time-lapse, since they are run in parallel! (since we are able to assume that context switching and other artifacts can be neglected). In consequence, the service time that we are using to calculate these statistics is:

$$\frac{servicetime}{mwt}$$

The queuing model M/M/1 computes the traffic intensity, which is the ratio between the arrival rate and the service rate. If this ratio is smaller than 1, the system is said to be "stable", otherwise it is "unstable". In our case, having a ratio bigger than 1 means that the middleware is saturated, i.e too many requests are coming in that can be processed, and a ratio of 1 is beeing obtained, when the throughput starts to flatten out. As we discussed in the *System overview* section, a ratio bigger than 1 is nearly impossible to achieve because memtier won't send more requests than what it receives back. However, small errors linked to statistics gathering can lead to having a ratio slightly over 1, even if it should be a little bit less than 1 in reality. For this reason, we will not be able to analyze the system when the ratio is getting close to 1, as the system will be described as "unstable".

We start by computing the different statistics for a middleware configuration with 8 threads for 2 virtual clients, which gives an arrival rate of 1568 requests/sec and a service time of 2813709ns per thread. As discussed previously, we use 2813709/8 = 351713ns as an input for the service time. The output from these calulations are found on the first line, the statistics collected from the middleware on the second line:[5]:

[5] P0: probability of having 0 jobs in the system
P1/P2: probability of having 1 respecitvely two jobs in the system

P0	**P1/P2**	**Jobs in system**	**Jobs in queue**	**response time[ms]**	**time in queue[ms]**
0.44	0.25/0.14	1.22	0.67	0.61	0.43
-	-	-	0.98	2.92	0.11

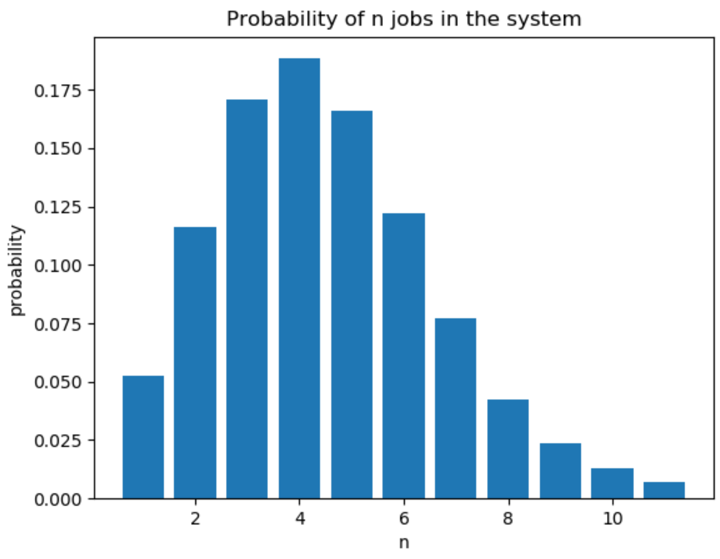
When comparing to the statistics[6], we see that the number of jobs in the system and number of jobs in the queue correspond! For the number of jobs in the system, since we modelled the system as an M/M/1 model, with the service time being serviceTime/mwt, the number of jobs in the system will be 1.22*mwt in reality, which is what we have in this configuration.
However, the time spent in the queue doesn't correspond at all to what we measured on our middleware. This is because our system can simply not be modelled correctly with a M/M/1 model: In this model, it is assumed that a "single server", i.e a single thread is handling the incoming requests. Assuming that mwt requests are being handled in a time period T (multiple threads) is the same as one request is being handled in T/mwt time (single thread) is not enough to model our system as an M/M/1. This is because multiple threads take requests from the queue in a round-robin fashion, whereas the single thread model takes one request at a time, executes it completely before taking another request.

7.2 M/M/m

To model our system as a M/M/m model, the experiment 4 statistics are used again. The M/M/m model has the same interarrival properties and queuing properties than the M/M/1 model. The only and crucial difference is that multiple "servers" are handling the requests being queued. In our case, multiple threads are handling the requests. A priori, this modelling seems to represent our system much better. We will see if this claim can be verified.
First of all, the same comment about the stability of the system applies to the M/M/m model: A ratio between the arrival rate and the service rate multiplied by the number of worker threads being bigger than 1 leads to an unstable system and the statistics cannot be computed. We compute the statistics with the same configuration as before, 8 worker threads, 1568 request/seconds for the arrival rate, and 2813709ns for the service time:

P0	Jobs in system	Jobs in queue	response time[ms]	time in queue[ms]
0.012	4.41	0.23	2.82	0.07
-	-	0.98	2.92	0.11

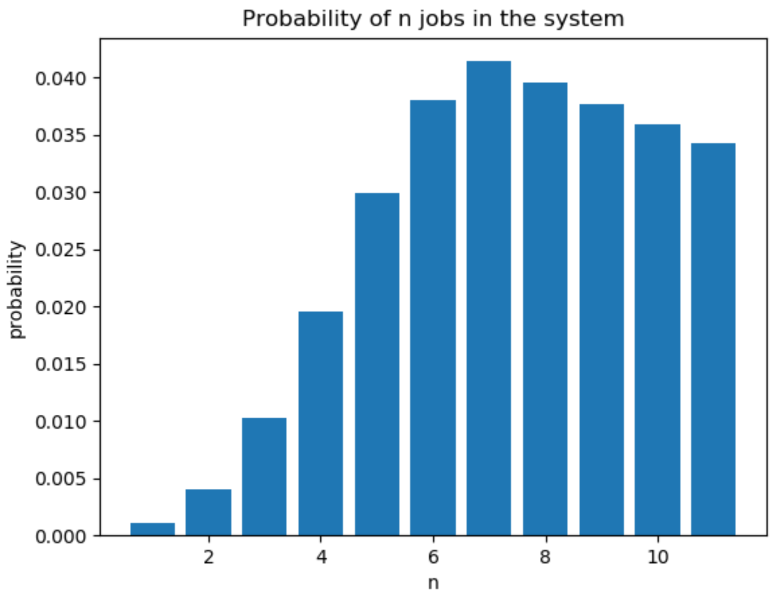
The probability distribution of the number of jobs in the system is plotted on the following chart:



[6]from the exp4 folder, mw01, thread8, rep3 file

For the M/M/m model, the response time and the queuing time are predicted right, with a very small queuing time and a response time. The mean number of jobs in the queue also corresponds to the gathered statistics. However, it seems with the chart that the system is underused, with a probability of only 5-6% that all the worker threads are in use. We want to verifiy this claim by taking a higher arrival rate with the same configuration, i.e 4 virtual clients, which gives an arrival rate of 2513 requests/second and a service time of 3036419ns. This leads to the following values:

P0	Jobs in system	Jobs in queue	response time[ms]	time in queue[ms]
0.0001	18.52	10	3.05	4.33
-	-	2.0	3.045	0.88



The system is now clearly used at its full rate, but the calculated statistics don't correspond as much to what we could observe in the middleware.
However, the model is able to predict that close to this arrival rate, the time in queue and the number of jobs in queue grows bigger and becomes the bottleneck of the system. In fact, when looking at the collected statistics for a one step higher workload, we see that the number of jobs in the queue has been measured to be 12.27, and the queuing time to be 5.27 msec. The reason why this model is only able to predict a given trend around this workload is because the calculations become very volatile around a ratio of 1, and thus the numbers inputed in the model need to be very accurate which is note the case in our middleware.
For example, the inputed number for the service time and the arrival rate for 4 virtual clients were respectively 3036419ns and 2513 requests/second, whereas the numbers for 8 virtual clients are 3080518ns and 2605 requests/second, which we can see are very close to each other. However, the second configuration leads to a slightly unstable system (ratio = 1.002), and the first configuration a slightly stable configuration (ratio = 0.97). Knowing that the inputs for the two configurations are very similar, and that an error has to be taken into account in the measurements, it is reasonable to compare the outputed calculations of the 1st configuration with the collected statistics for the 2nd configuration:

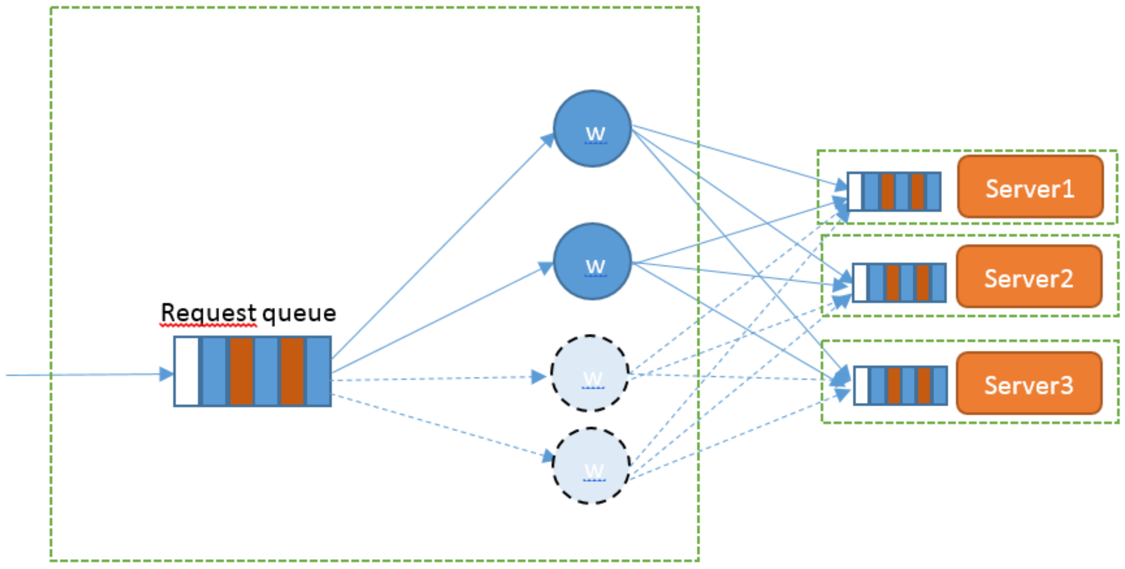
P0	Jobs in system	Jobs in queue	response time[ms]	time in queue[ms]
0.0001	18.52	10	3.05	4.33
-	-	12.27	3.081	5.21

Now we are able to see that the calculated outputs correspond very well to the collected statistics.

To conclude this part, we see that the M/M/m model is a much more suitable model for our middleware system than the M/M/1 model. When using the M/M/m model in a clearly underused configuration, the calculations are very close to the observed statistics. However, the M/M/m model outputs become very volatile when the traffic intensity (the ratio) grows close to 1, and thus, very precise statistics need to be inputed in the model to get corresponding statistics. This is not possible with our collected statistics, however it is possible to predict trends around a certain workload as seen previously. When being in a saturated configuration, the ratio grows systematically slightly over 1 due to some imprecisions and the model is not able to predict the correct values anymore. [7].

7.3 Network of Queues

For this last part we are modelling our system with a network of queue and trying to see the how some operationnal laws apply to it. We model our network of queue in the following way:



The request queue and the worker threads are being modelled as an M/M/m queue, whereas the queues at the different servers are M/M/1. As we discussed in the last section, an M/M/m model is the most accurate way to design the first part of the system. Since all the memcached servers are independent, one M/M/1 queue per server is what makes the most sense.
In our system, this network of queue will only confirm the informations gathered about the system through this report: every request goes into the same queue, and is treated by the same pool of worker threads. As discussed in the *System Overview* part, using a java *ThreadPoolExecutor* will use the worker threads equally as soon as they are free. Moreover, when looking at the service time for the different threads[8], we observe that they are all extremely close, which

[7]More configurations have been tested here and lead to the same conclusion. To test more configurations, just choose a stable workload, and run the script *mmm* found in the Scripts folder of experience 7, by putting the arrival rate, service time and number of worker threads to the good values

[8]see any file from experiment 3

is not a surprise since every thread has to execute the exact same request. In consequence, this means that every worker thread is visited the same. The servers are also used all the same amount: Recall that for a set operation, the request is beeing sent to every server, and that for a get request, the get operation are sent to a single server in a round-robin fashion.

This design enables us to compare the utilization of the request queue and the different worker threads with the utilization of the servers. We first calculate the different values in a generic way, by adapting the following naming convention :

- an index i or j: referes to a single component
- X [req/sec]: throughput of the system
- m: number of worker threads
- S [ms]: service time
- Q [ms]: queuing time
- ϵ: parsing time (which is small)

We first compute the the throughput per device by using the following formula for the throughput per device:

$$Xi = X * Vi$$

Device	Visit ratio	Throughput
worker thread i	1/m	X/m
server i	1/3	X/3

and thus the utilization for weach device, given by:

$$Ui = Xi * Si$$

Device	Throughput	Service time	Utilization
worker thread i	X/m	S+Q	(X/m)*(S+Q)
server j	X/3	S-epsilon	(X/3)*(S-epsilon)

Now we can follow this formula and find the different utilizations per device. We are using the configuration with one middleware and a read-only workload, 32 middleware threads and 2 virtual clients. This values corresponding to this configuration are:

- X: 822
- m: 32
- S: 2.37
- Q: 0.162745
- ϵ: 0.009322

whcih gives (note that a small conversion is beeing made to have ms both for throughput and times):

Device	Throughput	Service time	Utilization
worker thread i	26	2.53	0.0658
server j	274	2.36	0.646

We see that the utilization of the servers is 10 times as high than the utilization of the worker threads. This is of course because the middleware is underused with only 2 virtual clients. We now repeat the same tests with 16 virtual clients, 8 middleware threads and a write-only workload:

- X: 3222
- m: 8
- S: 2.48
- Q: 4.95
- ϵ: 0.007065

which leads to:

Device	Throughput	Service time	Utilization
worker thread i	402	7.43	2.986
server j	1074	2.48	2.666

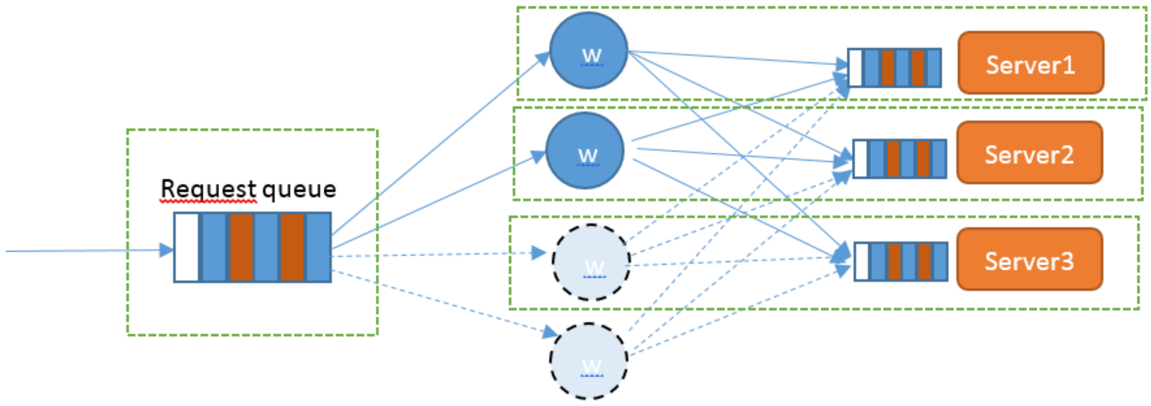
The statistics start now to show what we saw about the bottleneck of our system. One unique worker thread combined with the request queue has the same utilization than one server (And there are 8/3 more threads than servers!). By taking one step a higher workload (32 virtual clients), this claim can be proved:

- X: 3169
- m: 8
- S: 2.52
- Q: 15.2
- ϵ: 0.007065

which is:

Device	Throughput	Service time	Utilization
worker thread i	396	17.72	7.017
server j	1056	2.52	2.661

In a second part, we are modelling the system a little bit different to isolate the request queue, and verify even more that it is the bottleneck of our system. This is, our system will be as followed:



The request queue is now being modelled separately from the middleware threads as an M/M/1 queue. The servers are each beeing modelled individually with the worker thread currently communicating with this server. This is a reasonable way of modelling our system since as we saw previously, the service time of a middleware thread apart from the waiting time for the server's response is very small. With this modelling, we calculate the following generic results applying the same operationnal laws as before:

Device	Visit ratio	Throughput
request queue	1	X
server i	1/3	X/3

and:

Device	Throughput	Service time	Utilization
request queue	X	Q	Q*X
server i	X/3	S-epsilon	(X/3)*(S-epsilon)

When beeing applied to a high workload, i.e the last configuration used, we obtain the following:

- X: 3169
- m: 8
- S: 2.52
- Q: 15.2
- ϵ: 0.007065

which is:

Device	Throughput	Service time	Utilization
request queue	3169	15.2	48.168
server i	1056	2.52	2.661

The utilization of the request queue is now 18 times higher than the servers. For the previous modelling, the fact that we integrated the worker threads with the request queue to model a single M/M/m model attenuated this factor. But for this modelling, the bottleneck is definitely confirmed to be the request queue.

Finally, we want to have a quick look at a very important operationnal law, namely Little's law. Recall that Little's law is given by:

$$Lengthofqueue = arrivalrate \cdot responsetime$$

This law can be verified in our system , by for example using the configuration used lately, we have:

- arrival rate: 3.169 requests/ms
- m: 8
- S: 2.52
- Q: 15.2

which gives a queue length of 56, which is relatively close to the measured statistics (48).