Advanced Systems Lab Report
Autumn Semester 2017

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Grading

Section	Points
1	
2	
3	
4	
5	
6	
7	
Total	

1 System Overview

1.1 Overall Design

The overall design of the middleware created in this project is quite straight-forward. A single net-thread listens to a server socket and adds any requests sent to this socket to a blocking queue. A fixed number of worker threads then pull requests from the queue and process them one by one. Each of these worker threads is connected to all backend memcached servers at all times. When a request is being processed by a worker thread, this thread calls to at least one memcached server to handle the request. The only exception is an invalid request, such as an unknown command, in which case the middleware does not contact any backend servers.
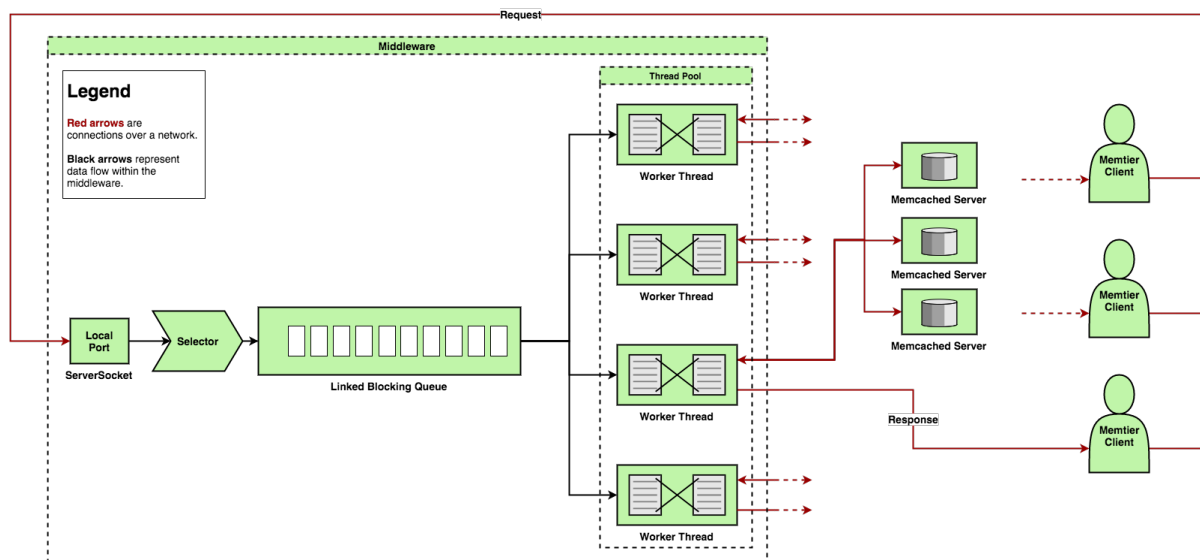

Figure 1: System Overview

As can be seen in figure 1, a selector is attached to the server socket in order to accept connections from clients. The key attached to the client connection is then passed with the request such that the workers can communicate the response back to the clients. The selector allows client connections to remain open until explicitly closed by the client. Hence the role of the selector is also to allow new connections and to add them to its internal register of client connections. Once in the internal register (the connection is accepted), the client can send a request which will be read by the net-thread and added to the queue with a reference to the client key. The worker threads then get requests off the queue and process them one by one. The workers first parse the request to get the command type. If the command is invalid, an error message is immediately sent back to the client associated with this request. Otherwise, the worker then communicates with the memcached server(s) in order to store or retrieve data. The servers' response(s) are then parsed again to check for errors and statistics, and a response, potentially merged, is sent to the client.

1.2 Selector

The selector serves as a register for connected clients. It is used as passing a socket channel in the queue as part of the request forces the connection to be closed at completion of the request. Hence the selector accepts connections from clients and registers all connected clients.

The selector then listens to the registered clients for messages sent to the server socket it is connected to and generates "read events" for each client sending messages to the socket. Simultaneously, the net-thread repeatedly checks for read events generated by the selector and reads data from the client associated with the event to a buffer. This buffer is then added as a request to the queue. Note that the selector key and a timestamp are added to the buffer to form a complete request on the queue. The use of a selector forces to use non-blocking IO on the client side. However, this is not a problem since any read event guarantees that data can be read from the socket, hence avoiding the use of reading loops.

1.3 Worker Threads

A thread pool executor of fixed size is used to organise the worker threads. This has the advantage that it reduces thread environment switching overhead if there is no need for an extra thread to be used. This could be the case when the connection to the memcached servers are extremely fast. In such a case, the executor will not use more threads than are available from the hardware as reusing the same thread to process the next request does not involve any overhead compared to switching to another thread to perform the same work. However, as soon as server service times increase, the thread pool allows to perform work on some thread while another is idle awaiting a response from memcached. Moreover, the thread pool executor has the advantage that if some thread crashed during the execution of the middleware, it will automatically be relaunched. Hence it should in theory provide more stability to the system.

The worker threads perform close to the entirety of the work within the middleware. The reason these threads perform the most work is that the work can be performed concurrently and, ideally, it is performed in parallel. In the initial design, even the reading from the socket was performed by the workers to avoid creating a buffer (containing the message sent from the client) for each request. However, this leads to request duplication as the read event is active as long as nothing is read from the socket, hence repeatedly adding requests to the queue if the initial request had not been read already. This is easily caused by even non-significant queue times. Therefore the design was changed, at the cost of creating a buffer for each request.

When launching a thread, two buffers are created. One is used for temporary data while the other contains the response from memcached to be sent back to clients. Note that all buffers used in the middleware are of size 16384 bytes as this allows for 10 keys of size 250 bytes and 10 values of 1024 bytes (and some margin) to be stored in the buffer. The temporary data buffer is mostly used to interpret individual responses from the memcached servers and its data is then added to the buffer containing the aggregate data for the client. Creating only two buffers for each worker, without adding buffers for the processing of each request, has the goal to reduce dead times created by the garbage collector. Exactly how individual request types are handled by the middleware and how the buffers are utilised is explained in a later section.

Each worker is connected to all backend memcached servers at all times. These channels are blocking to ensure that the worker awaits a response from the servers when reading from a channel. Should a worker crash, the thread pool executor will rebuild a thread to replace it and the connections to the servers should be reestablished. However, note that such a situation never occurred during testing.

1.4 Requests

All requests are built from the following:

- A buffer containing the data sent from the client. This is known when the request object is created.

- A selection key that refers to the client who sent the request. This is used to recover the channel to said client in order to send him the response. Note this has nothing to do with the memcached key used to refer to the data stored on the backend servers.

- A type which can be either:

  1. GET: a simple get request with a single key.
  2. SET: a simple set request with one key and the data to be set as the value for that key.
  3. MULTIGET: a get request with more than one key.
  4. INVALID: a request that does not conform to the protocol defining the format of the three commands above.

  This is not known when the request is created and will only be known once a worker parses the request.

- A boolean identifying the request as a hit. Note that the notion of hit is different for each type of request. In the case of a `get`, it simply identifies whether a value was returned by the memcached servers. In the case of a `set`, this represents whether a server responded with something different to `STORED`. In the cases of `multiget` and `invalid` request, this boolean does not have any meaning. `multiget` hits are handled directly as the responses from memcached are parsed.

- Several timestamps:

  1. The time the request is created. This is (obviously) known when the request is created.
  2. The time the request is dequeued. The worker updates this timestamp as soon as the request is taken from the queue.
  3. The time the request was transmitted to the servers. This timestamp is taken just before any messages are sent to memcached.
  4. The time memcached answered. This is taken once *all* memcached servers that were contacted for this request have answered.
  5. The time the request was completed. This is the timestamp taken when the complete response was sent back to the client.

All requests are parsed only at the worker level, hence the majority of the fields defined above are only known once the request is being processed by some worker.

When parsing a request, the first aspect that is checked is whether the request terminates with `"\r\n"`. Then the command is parsed up to the first occurrence of `"\r\n"`. The set of bytes preceding these two characters is converted to a string and the first word in said string is compared to known command words (i.e. `get` or `set`). Once it is established which type the command is, the rest of the command is checked for correctness. In the case of `get`, the number of arguments is checked in order to determine whether the command should be treated as a `multiget`. In the case of a `set`, it is checked if the data block attacked to the request is of the length specified in the command. If any of these tests fail, the command is flagged as invalid and an error string is sent back to the client. In this case there is no communication with the backend memcached servers as the request does not conform to the protocol.

1.4.1 Sets

Once a command has been dequeued, parsed, and established as type `set`, all worker buffers are cleared and the original request buffer is transmitted to all backend servers. The worker thread then awaits responses from the servers in the same order as he sent out the request. As we use blocking input/output on the server side, the same order is chosen as the first contacted server is likely the first to respond. Note however that if the connection to the first memcached server is significantly slower than other connections, this will result in inefficient time utilisation as the middleware will wait for this response first, even though the responses from other servers might already be available. Every response is then checked, and if anything other than `"STORED\r\n"` is returned from any server, that response is returned to the client and the `set` is flagged as a miss. The rest of the servers' responses are read in order to make sure all communication channels are cleared for the next request. In the case of a hit (i.e. all servers responded `"STORED\r\n"`),
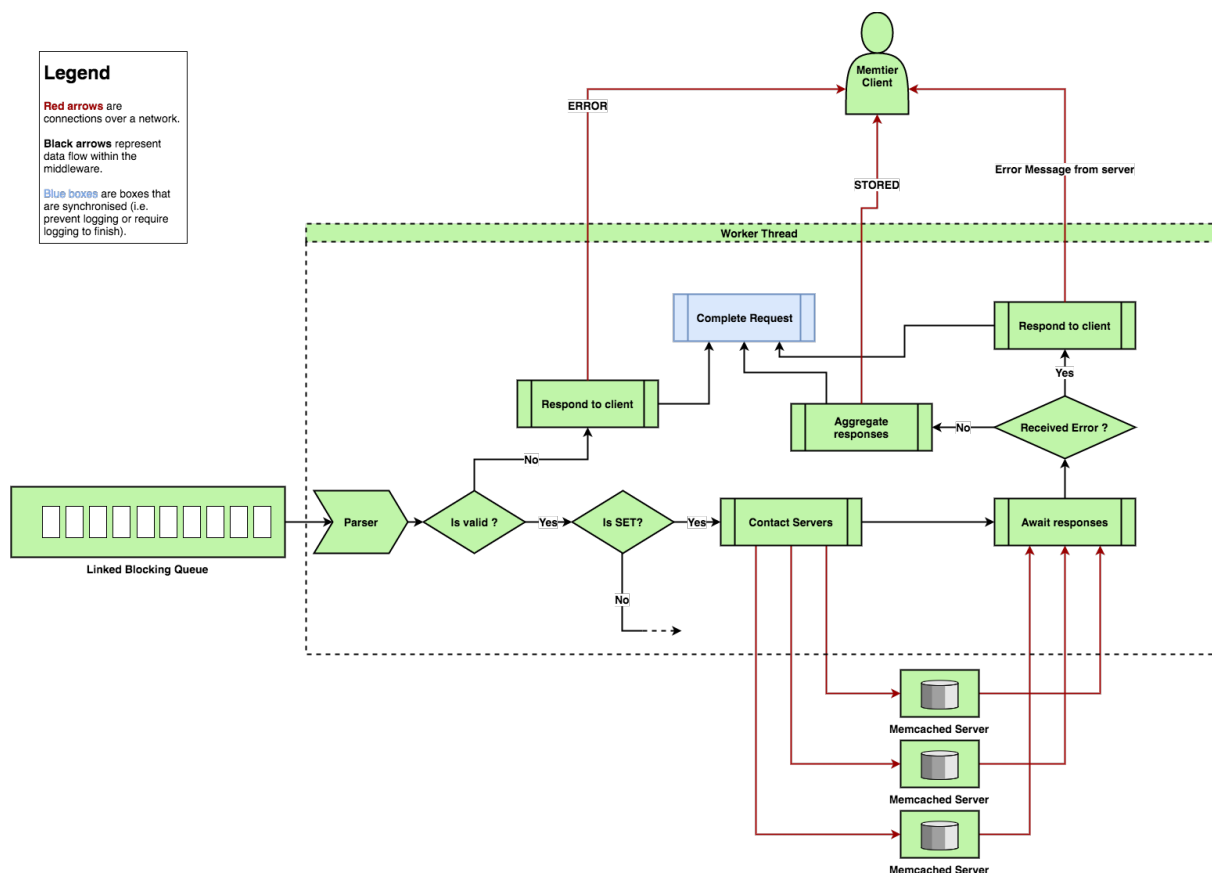

Figure 2: Handling of `SET` requests

this is relayed to the client and the request is completed. Request completion will be described under logging and thread synchronisation below.

Note that that during the time the request is handled, the appropriate timestamps are updated for the request.

1.4.2 Gets and Non-Sharded Multigets

As these requests are not sent to all memcached servers, load balancing is in order. To perform load balancing, a server is chosen by simply taking the least recently used server across all workers. Of course, this can be suboptimal if the least recently used server is still working on a large request and other servers have already freed after handling smaller requests. However, due to relatively strong variations in the network latencies, it is very difficult to predict the time needed for a server to process a request as these latencies account for the majority of the server time.
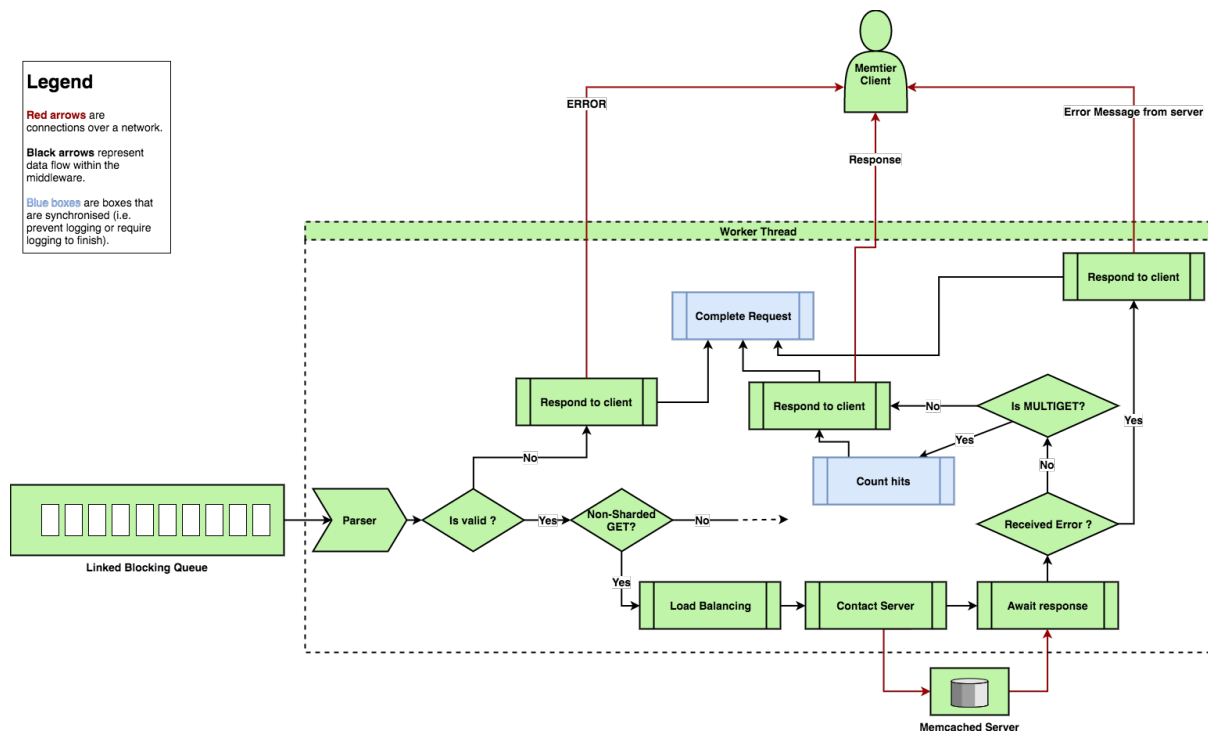

Figure 3: Handling of `GET` and non-sharded `MULTIGET` requests

The request, as it was received by the client, is then sent to the selected server. The worker awaits a answer and continuously reads from the channel until the response either ends with `"END\r\n"` or matches an error (anything ending with `"ERROR\r\n"`, i.e. also `"SERVER_ERROR\r\n"` or `"CLIENT_ERROR\r\n"`). Note that this does not create a hot loop as the channel reading is blocking.

If the request is of type `multiget`, the worker checks how many values were included in the response compared to the number of values requested in the command. This then determined the number of hits and misses of the request.

For a `get`, the response is compared to `"END\r\n"` and checked if it ends with `"ERROR\r\n"`. If neither is the case, the request is flagged as a hit.

Both for `multigets` and single `get`, the response is then relayed to the client and the request completed.

1.4.3 Sharded Multigets

In the case of a sharded `multigets`, the `readSharded(request, response_buffer, temp_buffer)` function is called. This function completely takes care of the handling of such requests with the exception of request completion. Sharded requests are handled in two ways (graphically shown in figure 4):

1. If the number of requested values is less than the number of available memcached servers, load balancing is performed and a single `get` is sent to a server. Again, the servers responses are interpreted in the same order as the servers were contacted. If an error is received from any server, `"ERROR\r\n"` is relayed to the client and the server channels are cleared for the next request. Otherwise individual responses are read into the temporary buffer, `"END\r\n"` is removed from the end of the buffer and the entire buffer is appended to the response buffer.

2. If the number of request values is larger than the number of available memcached servers, no load balancing is required as all servers will need to be contacted anyways. The processing is then performed as above.

Figure 4: Handling of sharded `MULTIGET` requests

When all memcached servers have answered, `"END\r\n"` is added to the response buffer and the response is relayed to the client unless an error occurred in one of the servers. The response

buffer is then converted into a string to check the number of hits. Note that this is performed irrespective of a server responding `"ERROR\r\n"`.

1.5 Load Balancing

As mentioned above, load balancing is performed in a simple round-robin way.

Source Code 1: Load Balancing

```
1   private static synchronized int getServer() {
2       return Worker.server++;
3   }
```

A synchronised function (listing 1) increments a static counter in the `Worker` class and returns this value. As this is a single integer, note that no leaking is performed. The worker thread having requested a new server is then responsible for taking the return value modulo the number of available servers. The result of this computation gives the least recently used server across all worker threads. Note that in this case least recently used has the meaning of "least recently requested from the load balancing mechanism". In the case of mixed loads, as `sets` are propagated to all backend servers, the server returned by this strategy might actually just have been used due to a `set` request. However, this technique still guarantees that the load for requests that do not require access to all servers is balanced.

In the case of sharded `multigets` where the number of keys is lower than the number of available backend servers, the function in listing 1 is called for each partial `get` request.

1.6 Logging, Request Completion and Thread Synchronisation

All statistical data relating to a request is stored within the request itself, hence the reserved fields for timestamps, type and hit flags. When a request is completed, the `complete(request)` private method of that worker object is called. This method then computes the required statistics and stores them internally in the corresponding worker object. Therefore, up until the completion of the request, no internal data of the worker was touched with the exception of `multigets` hit counting.

Every part of the workers that accessed internal statistics data is synchronised with respect to the worker object. Hence both the `complete(request)` and the `multiget` hit counting are synchronised. This ensures memory consistency when accessing the internal statistical data for logging. Thus all data should be consistent and no request should only be partially logged unless the logger kicks in between two blue boxes in figures 3 and 4. This can only happen during the handling of multigets and creates hits to be registered even though the request is incomplete. This is very unlikely to happen since close to no work is performed between any two blue boxes. Moreover, note that this does not affect any final statistics.

The logging is performed by a static function (of the worker class) that, when accessing the internal data of a worker in its argument list, locks that worker, hence preventing it from modifying its internal statistical data. This is done in order to get consistent interval information when logging. The signature of this function is shown in listing 2.

Source Code 2: Logging

```
1   public static String getRecord(ArrayList<Worker> workers, int queueLength);
```

Every second, the `getRecord()` function from listing 2 is called on all workers and gathers their statistical data to output what has happened in the last second. Note that this does not prevent the worker from performing work until it reaches either request completion or a multiget hit count update. Due to the fact that data gathering is relatively fast compared to the overall time needed to process a request and the server time, this usually does not affect performance. Moreover, note that not all workers are blocked, but only the one currently being accessed. This can create slightly offset data when the middleware is launched with a large number of workers as the last few workers might complete some requests while the data from the first worker is being read. However, this only affects the time interval, not the overall data, because the logger only gathers data from when `getRecord()` was called *on that worker*. Hence, even if the last worker completes more requests while the data from the first worker is being collected, these completed requests will not be considered the next time `getRecord()` is called on that worker.

Furthermore, `getRecord()` also takes care of clearing any histogram information stored in workers when running for the first time. This is to ensure that histogram data does not include requests completed during warm up time. The warm up time is set to ten seconds, therefore `getRecord()` is called ten seconds after the launch of the middleware and then again every second after that. This is performed by a scheduled executor service spawning a thread from the net-thread.

The analysis data is logged both to console and to an `analysis.log` file in the home directory. Note that the logs in the log file additionally contain timestamps. Moreover, the middleware logs system information such as interruptions, errors setting up sockets, connection request, etc. to `system_report.log` also in the home directory.

On top of that, when the `ShutdownHook` is triggered, statistics for individual workers is gathered and the histogram is printed. The statistic for individual workers include queue time, processing time, server time, total count, hits per second and misses per second for each request type. The final statistics layout is very similar to the one provided my memtier.

1.7 Terminology

This section describes the terminology used across all experiments unless explicitly specified otherwise.

Response time/latency as given by middleware
 This refers to the time between creation of a request when read from the server socket to the time the request is completed (i.e. the response has been sent to the client). Thus, this does not include the time the request and response spend in the network between the client and middleware hosts.

Processing time
 This refers to *all* time between the moment a request is dequeued and the moment the request is completed. Hence this fully includes server time.

Server time
 Server time refers to the time between the moment a request is forwarded to *any* memcached server and the time a response has been received from *all* necessary memcached servers. Therefore, in the case of sharded `multigets` and `sets`, it is measured from just before the first server is contacted to just after the last response is received. Note that this also includes network latencies between middleware and servers.

Standard deviation
   Unless explicitly stated otherwise, the standard deviation is the deviation between the average *interval* measurements of some specific software. These intervals are always one second in length. Hence the standard deviation of the latencies measured by 2 clients is the deviation of the results obtained from taking, each second, the average latency measured by both clients. The purpose of this is to show the deviation of the overall system from it's mean behaviour over the experiment time window.

Server
   A machine running an instance of memcached.

Maximum throughput
   Throughout the report, when maximum throughput is mentioned, note that the actual maximum measured throughput is meant. This does not infer that this throughput is achievable, as it does not take increases in response times into account. It simply represents the maximum measured throughput during the experiments.

1.8 Overall Experimental Design

All repetitions taken are at least 90 seconds long. The ten first seconds are evicted (warm up time) and the 80 next measurements are taken as the data. For client and server data, only the first eight seconds are evicted as the automation scripts allow two seconds for the middleware to boot properly before launching the clients. Note that due to `ssh` network latencies, the 80 second windows of measurements might not perfectly coincide between clients, middleware, and servers, but this should be insignificant compared to the overall length of a repetition. The effect of this can be seen in the slight differences of throughput between client and middleware data. However, as will be shown in the first middleware baseline, this is an irrelevant difference.

   The error bars used for all graphs are obtained from the standard deviation as described in the terminology subsection above. Deviation of the averages across repetitions are also available in the final data sheets (`/processing/final/<experiment_name>/data.csv`) but will not be used unless relevant. This would be the case if one repetition is deviating from the average significantly.

   On top of that, on all memcached host machines, memcached is always launched on a single thread for all experiments.

   In order to have a better understanding of system resource bounds and usage, two other pieces of software are used. Firstly, `dstat` is launched for each repetition in order to monitor CPU usage, network sends and receives, and disk reads and writes. This allows for a better overview of resource usage. Secondly, `iperf` is run at the very beginning of the experiments to measure network bandwidths between machines. This is only run once at the very beginning as all experiments were performed in a single run. Performing all experiments in one go ensures consistency in latencies between machines as no machines are reallocated between different experiments. In order to have an idea of these latencies, `ping` is also run between machines before each experiment for about five seconds. `ping` is not run during the actual experiments as it sends packets over a network whose bandwidth is a bottleneck in some experiments. Hence running it during experiments would restrict the system's performance even further.

1.9 System Stability

Figure 5 shows the stability of the system over time. The measurements shown are over the typical eighty second window used for all experiments in this report. The warm up time is excluded from this graph as explained in the previous subsection. The source of the data used to generate this plot is the data retrieved during the $2^k \cdot r$ analysis with one middleware, three servers, thirty-two worker threads, and a balanced mixed load (`1:1` ratio). Every data point is the average across all three repetitions. The error bars represent the standard deviation from between repetitions. Notice that, in this case, the throughput is the number of requests processed during the one second interval before the data point. Hence the data points at time 34 represent the number of requests handled between second 33 and 34 of the measurement window, and the average response times, server times and queue times of these requests.
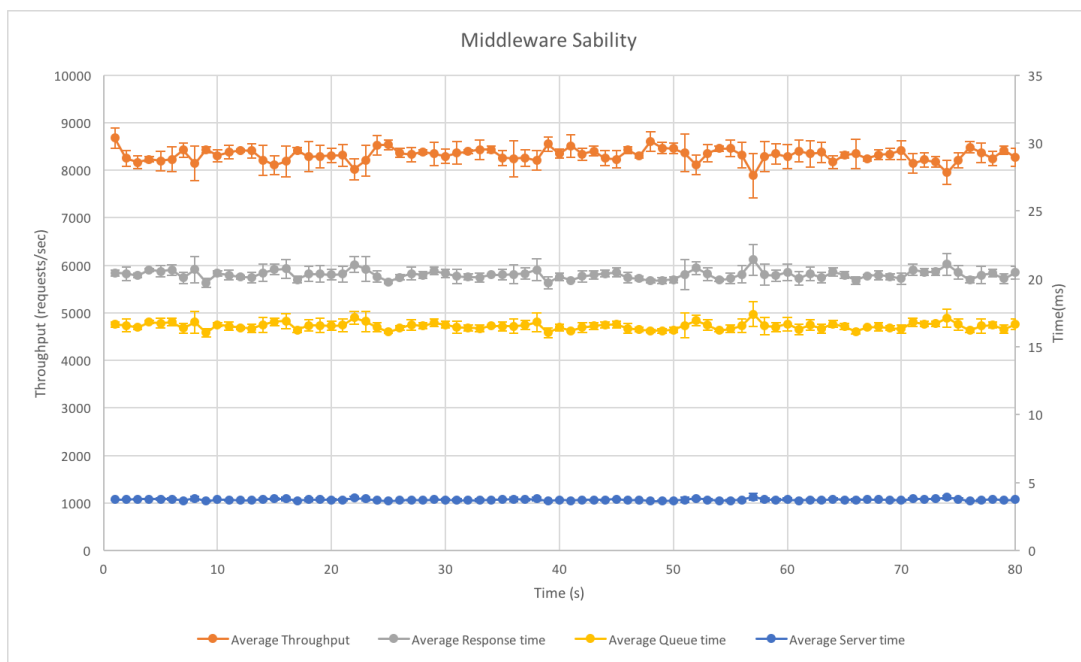

Figure 5: Stability of the middleware over time

Source: `processing/final/stability/servers_3/workers_32/ratio_1:1/stability.xlsx`

As one can observe, the system is stable over time.

2 Baseline without Middleware

The experiments under this section are performed without a middleware. The purpose of this is to establish some benchmark to determine the behaviour of memtier and memcached. For both read-only and write-only workloads, client ranges from two to 56 *per thread* were chosen. In the first experiment, a single memcached machine was connected to three client machines, all of which running on two threads.

In the second experiment, a single client machine running two instances of memtier was attached to two server machines. Both instances of memtier running on a single thread.

2.1 One Server

This experiment deals with the performance of memcached. Three client machines running memtier with two threads each are connected to a single memcached machine. Figure 6 shows the throughput of read-only and write-only requests with respect to the total number of clients.
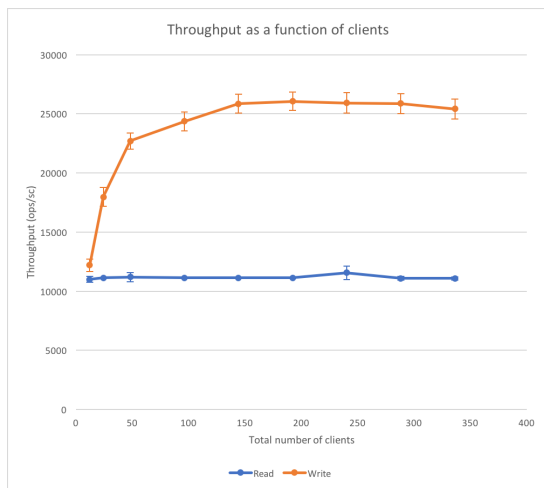

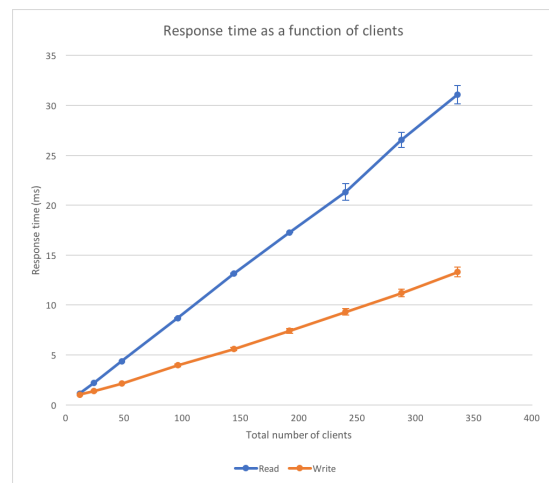Figure 6: Throughput as a function of total number of clients

Figure 7: Response time as a function of total number of clients

Figure 7 shows the respective response time with respect to total number of clients.

2.1.1 Explanation

First, note that the experiment obeys the interactive law. This can be seen in figure 8. The response time logged by the clients coincides perfectly with the response time computed by the interactive law. Graphs illustrating the interactive law will not be shown in later experiments unless the measurements used to graph throughput and response time do not obey operational laws.

First consider write throughput. Memcached seems to attain saturation at around 150 clients as shown in figure 6. Figure 9 indicates that the saturation level is reached due to CPU utilisation.

Second, for read throughput, saturation is already reached with 12 clients total. This is due to network bandwidth. `dstat` data indicates that the average network upload of memcached
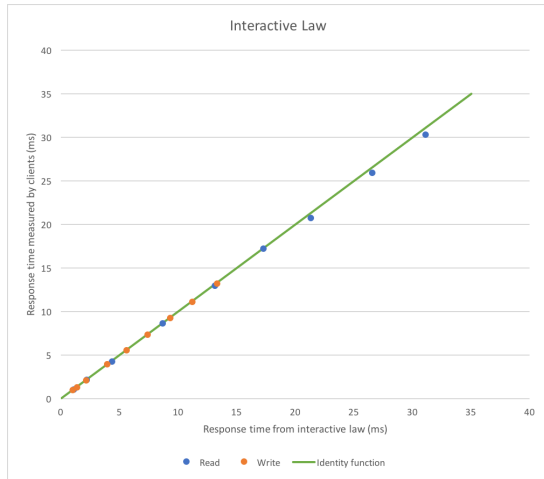
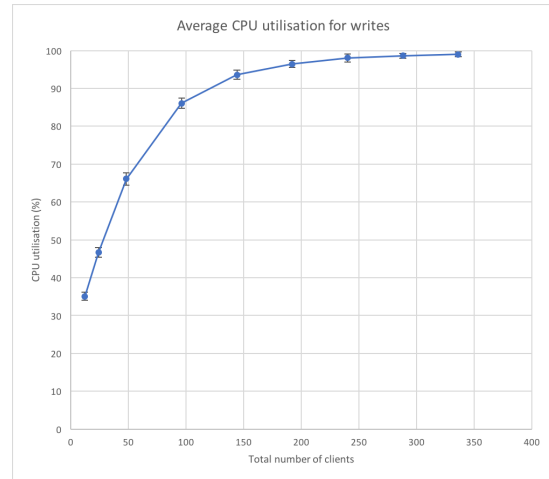Figure 8: Response time measured by clients versus interactive law response time

Figure 9: Average CPU utilisation based on total client count of memcached servers

is 12 megabytes per second[1]. From `iperf`, we know that the server upload bandwidth is also 12 megabytes per second (96.4Mbps$/8 = 12.05$MBps[2]). Hence memcached cannot handle more than around 11 thousand requests per second. This number makes sense since only hits occurred and data blocks are of size 1024 bytes. Then we have $11.000 \times 1024 = 11264000$ bytes of data uploaded to the network by the server. Note that this does not include any keys, `VALUE` and `END` statements, hence the number being slightly lower than the average network upload bandwidth measured by `dstat`.

2.2 Two Servers

This experiment has the goal to check for saturation levels of client machines. Figures 10 and 11 show throughput and response time as a function of the total number of clients respectively. Note that in this case, there is no significant difference in behaviour between read-only and write-only workloads. Still the interactive law hold as shown in figure 14. Note that on low ranges of response times, the response time measured by the clients is higher than the one computed by the interactive law. This is due to the fact that response times observed at low loads vary greatly between memtier instances on the same machine[3]. This is caused by different network latencies between the client machine and the two server machines.

2.2.1 Explanation

For both reads and writes, the memtier instance connected to the first server attains maximum throughput at 24 clients per thread[4]. However, the memtier instance connected to the second instance only attains maximum throughput at 48 to 56 clients per thread[5]. This causes the dent in figure 11 at 48 total clients. Beyond that point, the latency for the first instance of memtier starts to increase much more due to saturation hence dragging the average upwards.

---

[1] `processing/final/benchmark_memcached/dstat.csv`
[2] `logs/server1_network.log`
[3] `/processing/processed/benchmark_clients/**/clients.csv`
[4] `processing/processed/benchmark_clients/**/clients_24/clients.csv`
[5] `processing/processed/benchmark_clients/**/clients_48/clients.csv`

Figure 10: Throughput as a function of to-
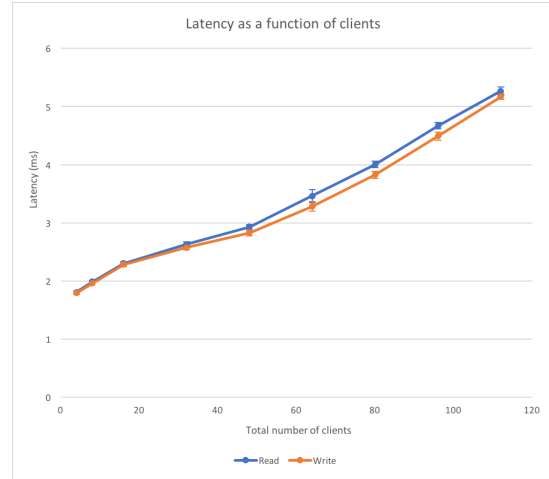tal number of clients

Figure 11: Response time as a function of
total number of clients

Thus, optimally, the first instance would run with 24 clients and the second one with 48 or 56
clients to achieve maximum throughput and low response time. As only configurations with the
same number of clients across all memtier threads are considered, the saturation point is at a
workload of 80 total clients for reads and for writes (40 clients per thread).

For any operation, the bottleneck is the network. Figures 12 and 13 show the data written
to network per second for reads and writes respectively. Note that for all graphs, averages are
taken across machines. Therefore, the data written to network per second given by the blue
line in figures 12 and 13 is the average *per server*.

In the case of reads (depicted in figure 12), one can see that the average data sent over the
network per server approaches the bandwidth limit (12.05MB per second[2]). This is the same
situation as in the previous experiment.

In the case of writes, the maximum bandwidth for client uploads is 24.125 megabytes per
second ($193\text{Mbps}/8 = 24.125\text{MBps}$[6]). Figure 13 shows that this is reached relatively fast.

In conclusion, the overall bottleneck in this experiment is the network. For both reads and
writes, the network does not allow the machines to reach compute power bounds.

2.3   Summary

In both experiments, writes generally allow to reach higher maximal throughputs (and hence
lower latencies). Generally, running around 70 to 80 clients per client machines also allows to
reach the highest throughput without over-saturation and increased latencies due to network
bandwidth limits or server compute power bounds. The only exception to this rule is read-only
workloads on a single server. In that case, the network bandwidth limit is already reached with
much lower client numbers.

The numbers in table 1 give the maximum measured throughputs, irrespective of when this
is obtained. In the best scenario, the client number with a single server is around 150 total
clients. This provides throughput very close to the numbers shown in table 1 but with lower
response times (saturation points). Similarly, for one load generating virtual machine, around
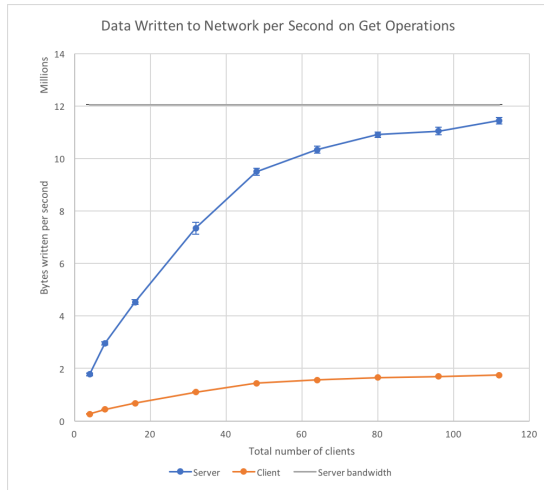
---

[6]`logs/client1_network.log`

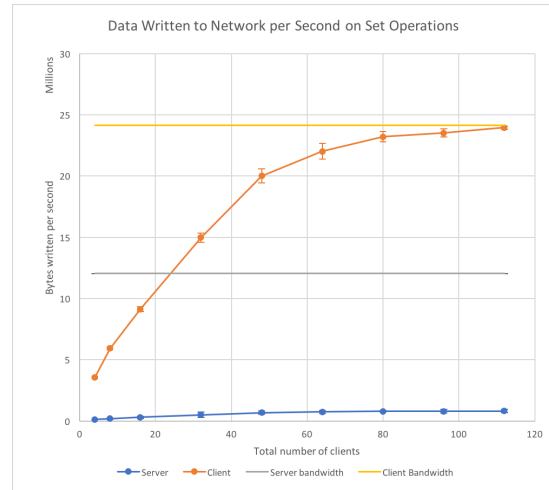Figure 12: Data written to network per second on reads

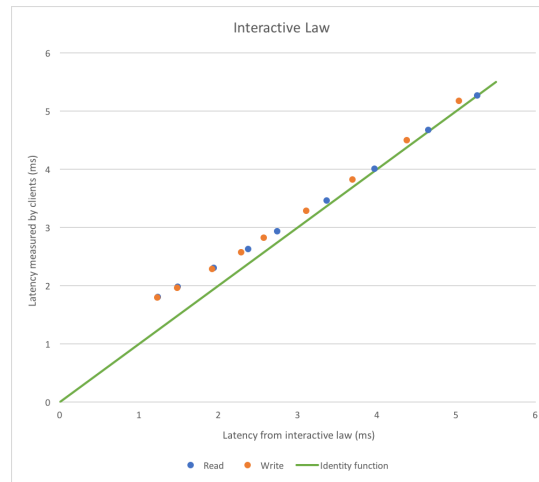Figure 13: Data written to network per second on writes

Figure 14: Latency measured by clients versus interactive law latency

70 to 80 clients generate enough load to achieve numbers close to the ones displayed in table 1 but with lower response times than with the configuration given in the table.

	Read-only workload	Write-only workload	Configuration gives max. throughput
One memcached server	11 558	26 056	Write-only; 200 clients
One load generating VM	21 283	22 264	Write-only; 112 clients

Table 1: Maximum throughput of different VMs

3   Baseline with Middleware

In this set of experiments, one load generating virtual machine and one memcached server are used. In the first experiment, a single middleware is used as intermediary between clients and the memcached server. In that case, the client machine runs a single instance of memtier with two threads and a range of two to 56 clients *per thread*.

During the second experiment, the client virtual machine is connected to two middleware machines, each getting requests from a single thread memtier instance. Both middlewares then use the same memcached server as backend.

In both cases, the middlewares are tested with eight, sixteen, thirty-two, and sixty-four worker threads *per middleware*. The backend server runs with a single thread configuration.

3.1   One Middleware

3.1.1   Reads

Firstly, figures 15 and 16 show that there is close to no mismatch between throughput data gathered from the client and from the middleware for read operations. The small differences in throughput are caused by the fact that the measurement windows might not coincide perfectly.
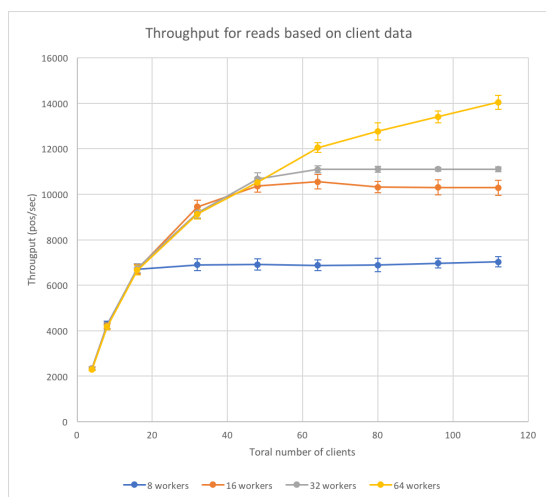

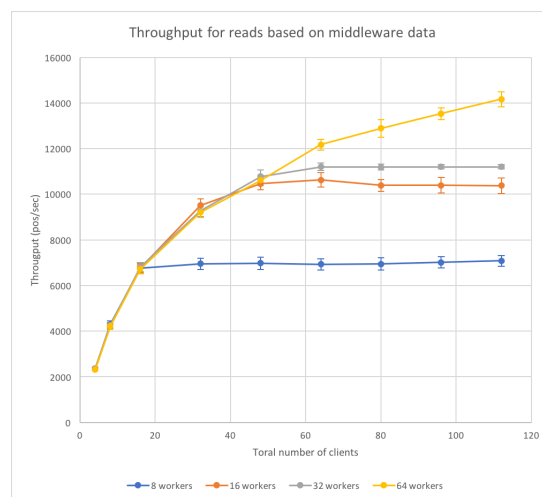Figure 15: Throughput as measured by the client machine for reads

Figure 16: Throughput as measured by the middleware for reads

The graphs displaying response time versus total number of clients for reads shown in figures 17 and 18 are very similar. Note that there is an initial offset of about one millisecond between the data provided by the middleware and the data provided by the client. This is due to network latencies. The response time measured in the middleware is measured from the moment a request is read from the server socket up to the point the response is sent back to the client. Hence it does not include the time spend in the network by both the request before arrival in the middleware, and by the response before reaching the client. This adheres to the ping data gathered before the experiment which resulted in an average of around 0.8 millisecond network latencies between those specific client and middleware hosts[7].

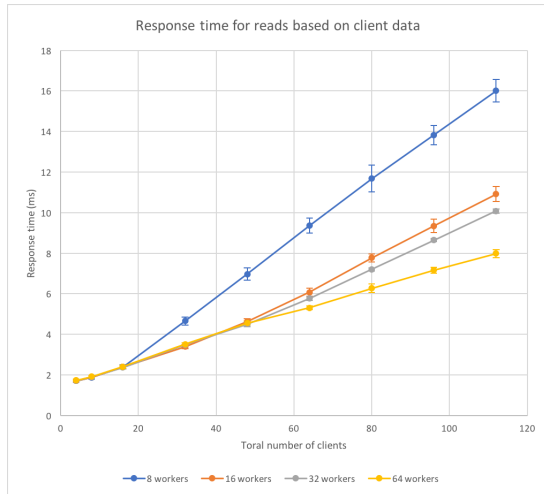[7]`logs/benchmark_1mw(2017-11-17_20h58)/mw_1_ping.log`

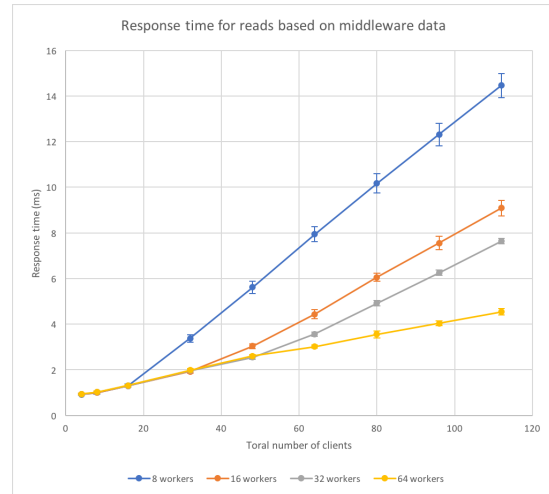Figure 17: Response time as measured by the client machine for reads

Figure 18: Response time as measured by the middleware for reads

This kind of comparison between middleware and client data will not be included in future experiments. In the case of discrepancies between data aggregated by the middleware and the clients, this will be made explicit and explained. Hence no such comparison implicitly means that the data has no significant enough mismatches to require explanations.

8 workers In the case of 8 workers, the saturation is reached due to time taken to process a request, i.e. the time from the moment the request is dequeued to the time the response is sent back to the client. Note that the average time spent in the network between client and middleware (both when sending a request and receiving a response), is about one millisecond. Now note that the average time taken to process a single request when using 8 workers is also about one millisecond. Hence, as long as less two times more clients than workers are sending requests, workers are efficient enough. This can easily be seen by considering that after a worker has completed a request for a client, it will take about 1 millisecond for another request from said client to arrive in the queue (due to network latencies), during which the worker can perform exactly one other request. Hence any number of clients superior to 16 (2×8 workers) will not increase throughput as all workers will necessarily already be busy. A consequence of this is increased queue times and thus increased queue lengths (as seen in figure 19). Therefore the middleware saturates at exactly 16 clients as can be seen in figure 18. This implies that the worker count is the bottleneck for this configuration. However, note this depends on the environment the middleware is used in, as shorter network latencies between middleware and servers will allow to reduce processing times, and thus higher throughputs for more clients.

Beyond the client number for which the middleware saturates, server times also stabilise. This is due to the fact that memcached has to handle only as many request per second as the middleware can process. This becomes constant beyond the point of saturation, hence server times become constant as well (see figure 20).

16 workers For 16 workers, we encounter the same problem as for 8 workers. However, since we now have 16 workers working concurrently, the phenomenon only occurs with a number of clients superior to 32 (2×16 workers). This is obvious when looking at figure 19. As a direct consequence of this, server times stabilise beyond this point (see figure 20). The change is not

as drastic as with 8 workers since the probability for slight changes in network latencies to result in a worker being idle increases with the number of workers. For example, due to a slight increase in network latency, more than 16 requests might be in the network between client and middleware, hence resulting in at least one worker being idle (by pigeonhole principle) if only 32 clients are used.

32 workers With this configuration, the network bandwidth becomes a problem. With 48 total clients, the memcached server has already nearly reached the network bandwidth limit. Again, this is can be computed manually as in section 2.1.1. As the throughput reaches levels close to 11k reads, the network becomes the bottleneck.

64 workers Note that this data is skewed. Obviously, if for 32 workers the network bandwidth was a bottleneck, increasing the number of workers should not increase throughput as indicated in figure 18. The reason that throughput can increase beyond the levels without middleware is the following. The experiment was run on a rather large range of clients and all read repetitions were performed collectively. Hence during several hours the only operations sent to memcached were reads, this resulted in all cached data being evicted while running the experiment with 64 workers. Table 2 shows at what point exactly the data was evicted.

Ratio	Sharded	Workers	Client per thread	Hit/request ratio
0:1	false	64	2	1
0:1	false	64	4	1
0:1	false	64	8	1
0:1	false	64	16	1
0:1	false	64	24	0.963838567
0:1	false	64	32	0
0:1	false	64	40	0
0:1	false	64	48	0
0:1	false	64	56	0

Table 2: Data Eviction

Source: `/processing/final/benchmark_1mw/data.csv`

Therefore note that beyond 48 clients (24×2 threads), memcached responses contain no more data, hence effectively removing the network bandwidth bound. In fact, average network sends per second are reduces from 11MB to slightly more than 8MB[8] per second even though throughput rises as indicated by figure 16. This also causes queue lengths to increase slower than normally as more requests per second can be handled by memcached. This can be seen in figure 19. In the case of server times, they are first reduced due to less data having to be sent over the network, then increase beyond the level of 32 workers (figure 20) simply because much more requests have to be handled by memcached, hence increasing response time of the server. Normally, if the data eviction had not occurred, throughput with 64 workers should have behaved similarly to throughput with 32 workers.

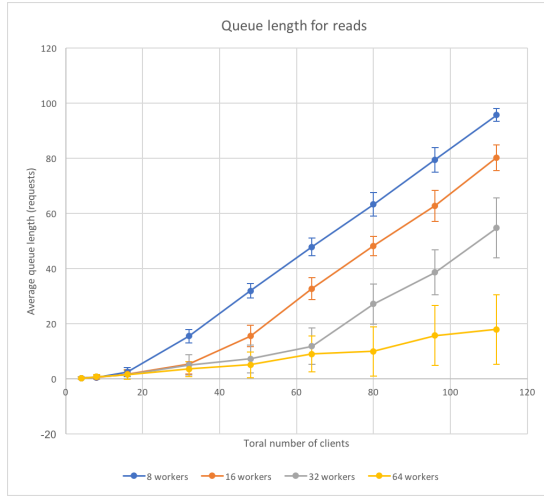[8]`processing/final/benchmark_1mw/dstat.xlsx!Sheet1`
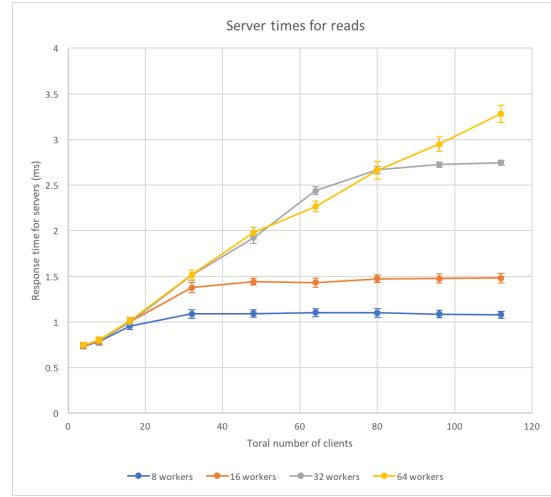
Figure 19: Queue length for reads

Figure 20: Server time for reads

3.1.2 Writes

As discussed above, only middleware data will be shown in this section as it does not differ from client based data. Figure 21 shows throughput as a function of number of clients for write operations. Similarly, figure 22 shows response time as a function of total client number for write operations based on middleware data.
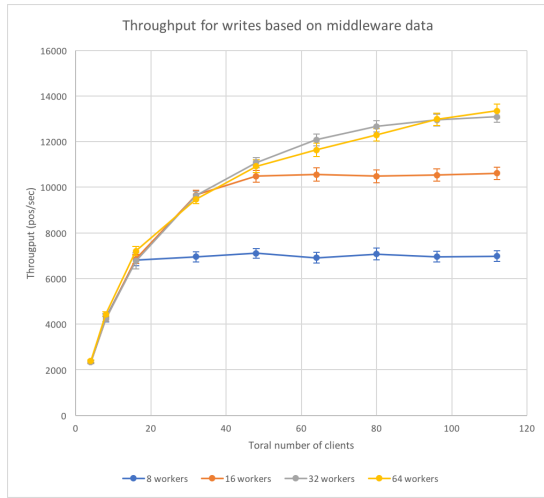
Figure 21: Throughput as a function of clients for writes
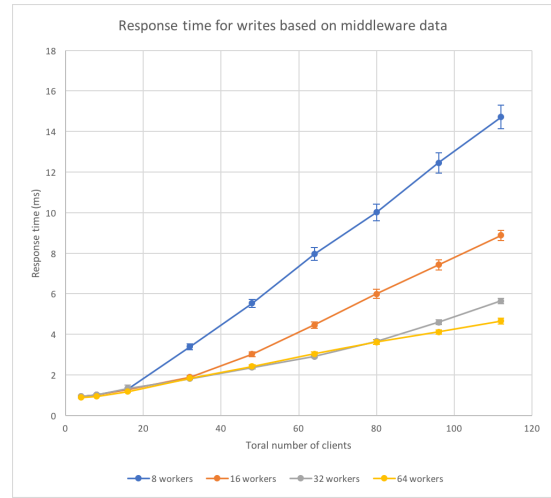
Figure 22: Response time as a function of clients for writes

All worker counts With 8 workers, the same issue as for reads with 8 workers is encountered. One can clearly see in figure 21 that past 16 clients the system is saturated. Unsurprisingly, as network latencies between client and middleware, and between middleware and server are similar to the ones for reads, the throughput attained when saturated is comparable. Note that the same problem is encountered for all worker configurations. The server response time increases as throughput increases (see figure 23), just as presented in the server baseline and shown in figure 7. This causes increasing processing times in the middleware thus reducing

the speed up by doubling worker counts. Moreover, the network latencies between client and middleware increase in parallel to this, hence preserving the ratio of about 2 clients per worker before reaching saturation. For example, figure 24 shows the change in server times and network latencies between middleware and clients. Note that the network latencies are computed by taking the difference in response time measured by the middleware and the response time measured by the client machine. The increase in this latency is likely due to the fact that the net-thread in the middleware cannot read requests from the network fast enough. Thus, when a large amount of requests arrive in very short time windows, some of the request need to wait a relatively long time before being read by the net-thread and added to the queue.
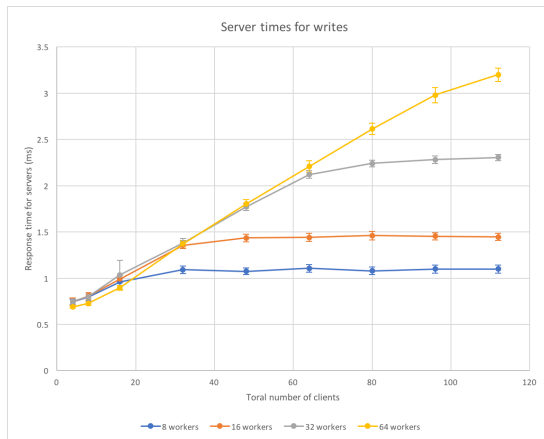
Figure 23: Server time (time in network + time in server) for writes
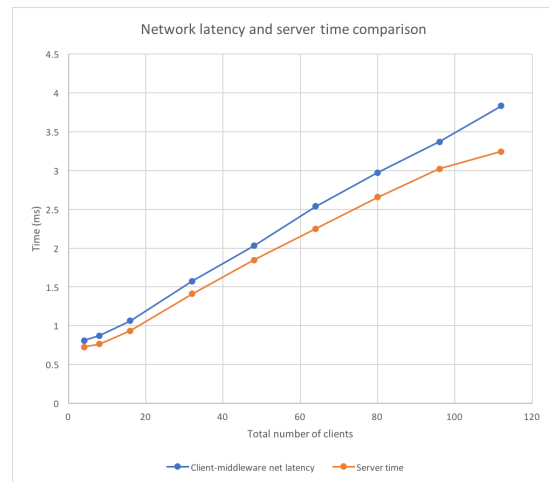
Figure 24: Network latency and server time for writes with 64 workers

3.2 Two Middlewares

In this subsection, two middleware machines are used. Each is connected to the same memcached server and a single load generating virtual machine hosts clients. Two instances of memtier, each running on a single thread, are connected to the two middlewares and the client count per thread is increased to study its impact on the behaviour of the system.

3.2.1 Reads

Figures 25 and 26 show the throughput and response time as a function of client count for reads. Figure 25 shows the total throughput across both middlewares. Once again, data was evicted while the experiment was running. This causes throughput with 64 workers to increase above levels with other configurations. This is again due to the fact that the network bandwidth is the bottleneck for 8, 16, and 32 workers. The server cannot upload data fast enough to handle more requests. However, as data gets evicted, requests require less data to be uploaded by the server (due to empty responses), hence allowing more requests to be performed per second. Average hit to request ratio drops from 79.6% to 8.7%[9] between 16 and 24 client runs with 64 workers. This results in a drop from 11.6MB to 2.6MB[10] of data per second uploaded by the server. Therefore, higher throughputs are possible.

[9]`processing/final/benchmark_2mw/benchmark_2mw.xlsx`
[10]`processing/final/benchmark_2mw/dstat.csv`
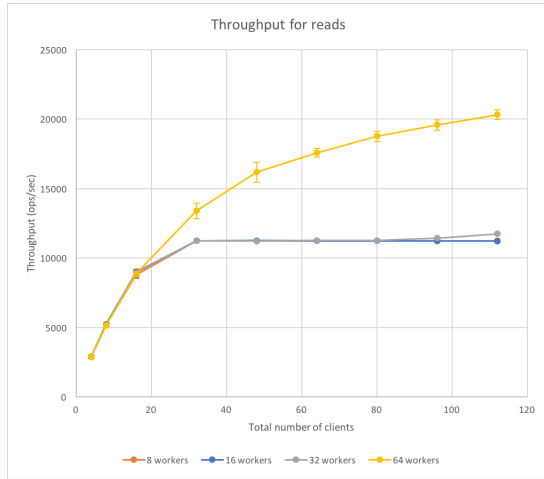
Figure 25: Throughput as a function of clients for reads
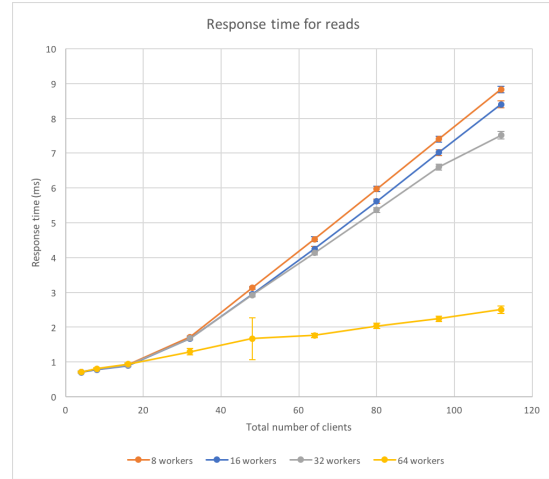
Figure 26: Response time as a function of clients for reads

3.2.2 Writes

Figure 27 clearly has a dent with 16 workers. This is caused by a sudden increase in network latencies between the middleware and the memcached server. When testing with 16 workers, the last repetition with 32 clients per threads and the first repetition with 40 clients per thread experienced server times more than 2 times higher than normal[11]. The standard deviation in throughput and response time between repetitions hence increased thirtyfold between 24 and 32 clients[12]. It actually reached normal levels again only when testing with 56 clients per thread.

The increase in network latencies between middlewares and server is likely caused by a short burst in network traffic on Microsoft Azure resulting in higher network latencies between middlewares and server. Hence processing requests takes more time resulting in lower throughput and higher response times.
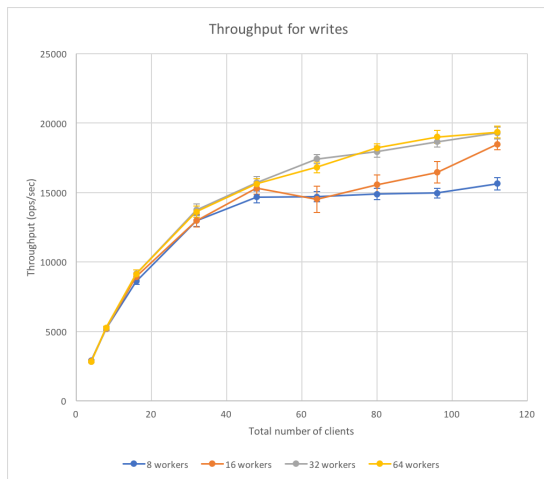
Figure 27: Throughput as a function of clients for writes
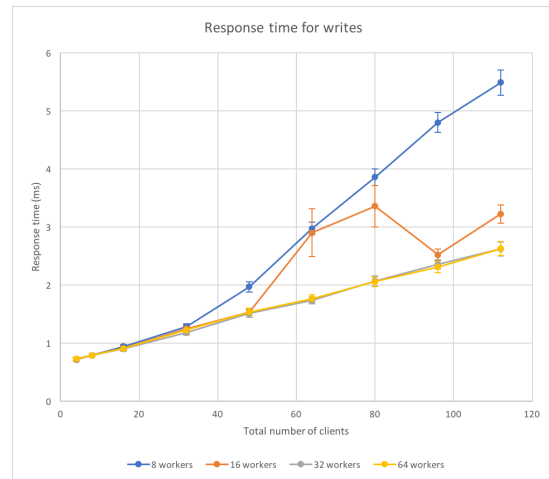
Figure 28: Response time as a function of clients for writes

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[11] `processing/processed/benchmark_2mw/ratio_1:0/sharded_false/workers_16/clients_32/mws.csv`
[12] `processing/final/benchmark_2mw/data.csv`

With these configurations, the bottleneck remains the workers. As network latencies are significant between the middleware and the servers, workers remain idle most of the time, waiting for a response from the contacted servers. This results in long service times from the workers, hence giving an upper bound on throughput. Adding workers allows for more work to be performed in parallel in the middleware as CPU utilisation required to run the workers is far from the maximum. Of course, this can be drastically improved by reducing the network latencies between the middleware and the servers.

Figure 29 shows the difference in response time measured by the client and the middlewares. The dent for 16 workers is due to the fact that middleware 2 had very low server times at 96 clients[13]. This lead to reduced response times for said middleware, decreasing the average response time of the middleware and increasing the difference in measured response times between client and middlewares.

In all cases (8, 16, 32 and 64 workers), the response time difference between client and middlewares increases steadily. This suggests that the net-thread cannot read the requests fast enough to put them on the queue, hence creating latencies between client and middlewares. The reason the increase is less significant for 8 clients is that response time increases much more than for 32 or 64 clients. Hence less requests are in the network between client and middlewares at any given time, thus making the net-thread reading less of a bottleneck.
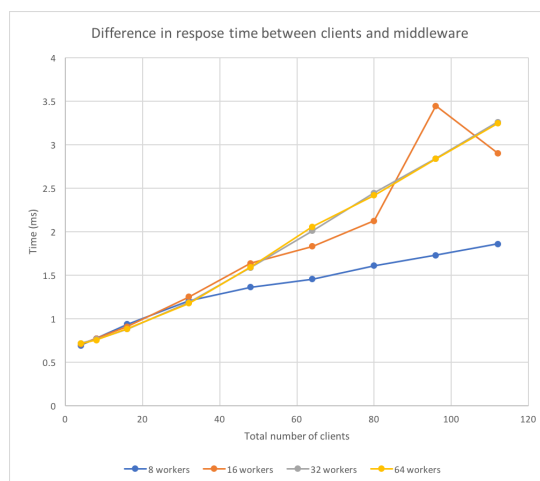
Figure 29: Difference in response time between clients and middleware for writes

3.3 Summary

Tables 3 and 4 show the maximum throughputs and the corresponding response times as measured by middlewares and the client machine. Note that for reads, the maximum throughputs were chosen irrespective of miss rates, hence the figures are much higher than could be expected with low miss rates. If hit rates were taken into account, the maximum throughput for reads would be comparable to the one in figure 1 for a single server. This would be the case for both a system with a single middleware, and one with two middlewares. However, due to high miss rates, the server does not require much data to be sent back to the middleware(s). Therefore the network bandwidth no longer creates a bottleneck, allowing to obtain higher throughput.

Moreover, the system with two middlewares performs nearly twice as well as the system

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[13]`processing/processed/benchmark_2mw/ratio_1:0/sharded_false/workers_16/clients_48/mws.csv`

with a single one. Response times are reduced by about two milliseconds both as measured by middlewares and by clients. Average time spent in queue is also reduced considerably. This directly follows from the fact that less requests have to be handled *per middleware* in a system with more middlewares.

	Throughput	Response time	Average time in queue	Miss rate
Reads: Measured on middleware	14 162	4.54	1.21	100%
Reads: Measured on clients	14 049	7.98	n/a	100%
Writes: Measured on middleware	13 343	4.66	1.41	n/a
Writes: Measured on clients	13 208	8.49	n/a	n/a

Table 3: Maximum throughput for one middleware

	Throughput	Response time	Average time in queue	Miss rate
Reads: Measured on middleware	20 303	2.50	0.47	100%
Reads: Measured on clients	20 113	5.60	n/a	100%
Writes: Measured on middleware	19 349	2.63	0.46	n/a
Writes: Measured on clients	19 205	5.87	n/a	n/a

Table 4: Maximum throughput for two middlewares

4 Throughput of Writes

During this experiment, three load generating virtual machines, running two instances of memtier each, are connected to two middlewares. Each instance of memtier runs on a single thread. The number of clients per thread varies between two and 56. The two middlewares are hosted on different virtual machines and are connected to three backend memcached servers. Configurations with eight, sixteen, thirty-two, and sixty-four worker threads *per middleware* are used.

Once more, all instances of memcached run on a single thread.

As the title indicates, the experiment is run on write-only workloads with a range of different client numbers.

As shown in figure 30, each increase in workers increases the overall performance of the system. The middlewares already saturate at 24 clients when running with 8 workers. This follows from the time taken for servers to respond to the middlewares. Note that the base time spent waiting for servers is much higher when using three backend servers compared to a single memcached server. This is caused by the fact that if one of the three servers is very slow (due to network latencies or CPU bounds), the worker is idle waiting for a response. Moreover, much more data has to be sent over the network since *all* data from `set` requests is sent to all servers (not just parts such as in sharded `mutliget` requests). Hence, it requires the middlewares to send exactly three times as much data as with a single server. This results in longer response times and, by operational laws, in lower throughput.
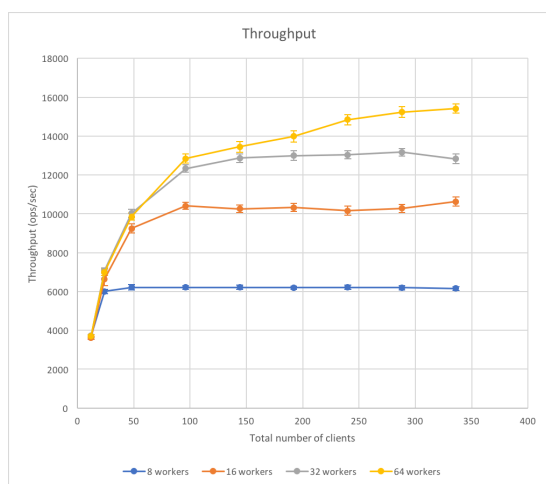
Figure 30: Throughput as a function of clients
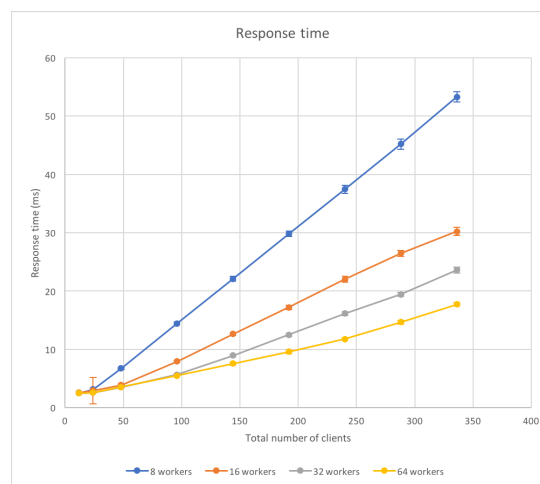
Figure 31: Response time as a function of clients

Note that the drop in throughput compared to single server systems is very significant. In figure 27, one can see throughput levels above 10 thousand requests per second. In the current case, 24 total clients results in barely over 6 thousand requests per second (figure 30). When comparing the time spend processing a request for both these system setups, one can see that the actual time spent processing (without time spent waiting for servers) is about the same at 0.03 milliseconds[14]. However, the time spent waiting for servers changes considerably. With three servers, this ranges from 2.38 to 2.55 milliseconds over the entire range of clients[15]. With a

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[14]`processing/final/*/data.csv`
[15]`processing/final/throughput_writes/data.csv`

single server, the server time is less stable but also much lower, increasing from 0.63 milliseconds for 4 clients to 1.41 milliseconds for 112 clients[16].

The stability in server time for three backend servers is only present for low worker count though. When running the middlewares with more workers, server times increase with client count as seen in figure 32.

This general offset in server times when using three backend servers results in earlier saturation of the middlewares. Taking the configuration with 8 workers as an example once more, the system with a single memcached server saturates at 48 total clients (24 per middleware) as seen in figure 27. In the case considered during this experiment, the system already saturates at 24 total clients (12 per middleware) as seen in figure 30.

For all configurations, the bottleneck is the worker count. Once more, the time spent in the network and processing on the servers creates a lower bound on service times of the workers, resulting in idle waiting the majority of the time. As no compute power is required for an idle worker, increasing the number of workers allows more parallelism, increasing throughput. However, due to the increase in server time, doubling the number of workers does not quite double the throughput at saturation level. On the other hand, note that when switching from 8 workers to 16, the server time does not increase considerably, hence allowing for nearly twice the throughput at saturated levels (from about 6 thousand to about 10 thousand requests per second).

Figure 33 shows how queue length varies with increases in client counts. On this graph, one can distinctly see how an increase in the number of clients on a saturated system simply increases the queue length linearly. For 8 workers, this happens beyond 24 clients; for 16 workers, beyond 48 clients; for 32 workers, beyond 96 clients; and for 64 workers at around 192 clients.
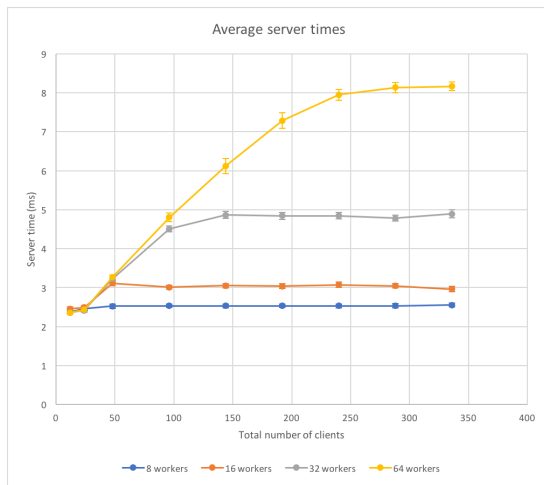
Figure 32: Average server times as a function of total number of clients

Figure 33: Queue length as a function of total number of clients

Table 5 shows maximum throughput as measured by middleware and clients as well as more information at that level of throughput. Note that for the throughput derived from the middleware response time, the following formula is used:

$$X = \frac{N}{R + Z}$$

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[16]`processing/final/benchmark_2mw/data.csv`

The think time used (Z) is 0 as technically it would be equal to the time taken to send a response back to the client and the client sending a request back to the middleware. However, this would mean that $R + Z$, with R being the response time measured by the middleware, is equal to the response time measured by the client. As this obviously follows operational laws, it would be redundant to compute this.

	WT=8	WT=16	WT=32	WT=64
Throughput (Middleware)	6218	10 624	13 175	15 421
Throughput (Derived from MW response time)	6412	11 115	14 814	18 971
Throughput (Client)	6164	10 529	13 060	15 261
Average time in queue	34.88	27.24	14.62	9.50
Average length of queue	108.9	145.3	97.7	74.5
Average time waiting for memcached	2.53	2.96	4.78	8.17

Table 5: Maximum throughput for the full system

The figures displayed in table 5 clearly show that 64 workers provide the highest throughput. Moreover, the gap between measured throughputs and throughputs computed with the interactive law increases with the number of workers. This is caused by the increase in difference between the response time measured by clients and the response time measured by the middlewares. That difference increases due to the fact that the net-thread has less available resources to read from the network as more worker threads read and write from network, hence creating a queue in the socket server. However, this is not a bottleneck as average queue lengths are still quite high. This would only become a problem if workers were able to process requests faster than the net-thread can read requests from the socket. However, this is by far not the case due to the time spent waiting for server responses.

5 Gets and Multigets

In this section, three load generating client machines and three servers are used. Each load generating virtual machine runs two instances of memtier on a single thread with two clients each, and connected to one of two middlewares. Between repetitions, the number of keys requested by `multigets` is increased and tested on middleware configurations with both sharded and non-sharded reads. All middleware configurations use 64 clients.

Note that in order to correctly measure response times for `multigets`, the load used to portrait the data used below is read-only. Default load was used to check for behavioural changes in the middleware for mixed loads. However, the histograms acquired from the clients showed that the handling of `get` and `multiget` requests was unaffected by a mixed load. Therefore, as the middleware only outputs a single aggregate histogram for all types of requests, a read-only load is used in the analysis.

All standard deviations used for percentile information are computed as the deviation of all percentile measurements. Hence an average is taken across all repetitions, memtier machines, and memtier instances on each machine, and the standard deviation of these (18) measurements is used in the graphs for this section. Therefore, the error bars represent both variations between repetitions and variations across memtier instances.

Moreover, note that the actual sizes of the `multigets` is equivalent to their maximum size as the ratio was intentionally modified during the testing to ensure consistency. Therefore, from this point onwards, maximum key size will be equivalent to average `multiget` size.

On top of that, the bottleneck is the same for both sharded and non-sharded `multigets`. For all request sizes, the bottleneck is the client count. The network bandwidths are not reached and we have way less clients than workers. This means that at all times, some workers are idle waiting for requests to be read by the net-thread. Moreover, the servers have very low CPU utilisation, indicating they could handle more requests. Clients CPU utilisation is also very low as they can generate many more requests per second, but by the design of memtier (each client awaits a response before sending a new request), only very few requests are generated at any one time. Note however, that for `multigets` of size nine, the network write bandwidth of the servers is nearly attained. The average network write (for both sharded and non-sharded cases) is above 10MB/s[17]. Hence, slightly increasing the client count would create a new bottleneck in the network.

5.1 Sharded Case

Figures 34 shows the average response time as measured by clients and response times for 25th, 50th, 75th, 90th and 99th percentiles.

First, consider that a sharded `get` with a single key is equivalent to a non-sharded `get` of a single key. Hence the first data points are not representative of "typical sharded behaviour". Second, note that on actual sharded requests, the average response time is comparable to the response time from the 75th percentile. This indicates that the 25% of requests with the highest response times actually have much larger response times than the average, therefore resulting in a mean well above the median (50th percentile). The reason for this phenomenon is that using three servers increases the likelihood of one server being slower than average. In order to have a small server time, all contacted servers need to have low individual server times. This

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[17]`processing/final/get_and_multigets/dstat.csv`
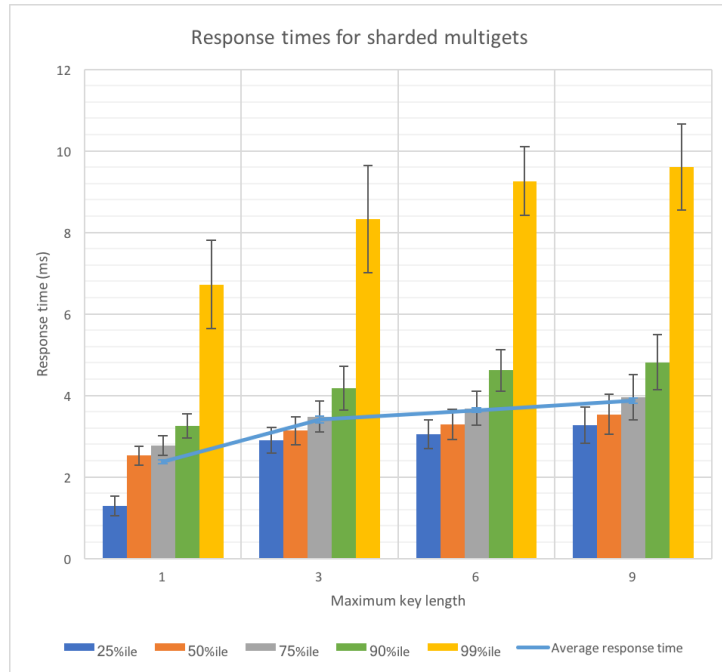
Figure 34: Response times for sharded `multigets`

of course is much less likely than at least one server having a relatively long response time. In the latter case, the worker processing the sharded `multiget` is required to wait for the response of that server, significantly impacting overall response time for the client.

5.1.1 Explanation

Having only twelve total clients (2×6 instances of memtier) distributed over two middlewares running both with 64 worker threads implies that workers are never completely utilised. In fact, most workers are idle during this experiment as too few requests are sent to the middlewares to require the usage of all workers. This is quite inefficient as those workers require memory and can create an unnecessary overhead with such a small number of clients.

Server response time still represents nearly the entire processing time. As long as this does not decrease, no higher throughputs are possible with a constant number of clients. However, for `multigets` of size 9, increasing the clients is actually very unlikely to improve throughput as the average amount of data sent to the network per server (10MB per second[18]) is already reaching the maximum bandwidth.

The general increasing trend in average response times measured by the clients is due to increased server times as the maximum key number increases. This follows as a `multiget` with twice the number of keys requires twice as much data to be sent over the network and, unless memcached optimises `multigets`, twice the compute power for memcached.

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[18]`processing/final/get_and_multigets/dstat.csv`

5.2 Non-Sharded Case

In the non-sharded case, average response time is comparable to the 50th percentile response time (as seen on figure 35). This follows from the middlewares only contacting a single server for each request, hence the likelihood of a server behaving better is comparable to the likelihood to a server behaving worse. As the worker thread handling the request does not need to wait for additional servers, these two scenarios balance out resulting in a mean relatively close to the median. However, note that the overall spread of percentile response times is larger than the one measured in the sharded case. This implies that the spread of the response time distribution is relatively broad, even if the average is close to the median.
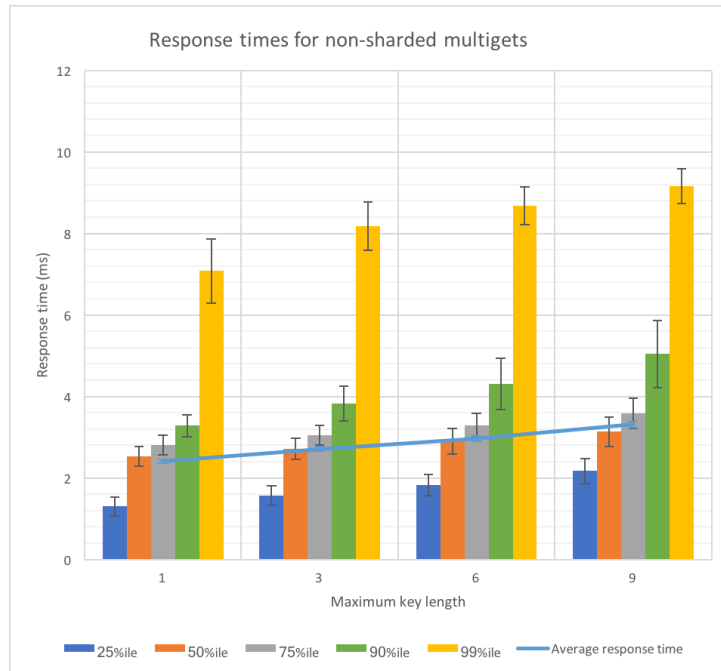
Figure 35: Response times for non-sharded `multigets`

5.2.1 Explanation

As with the sharded case, the relatively low client count compared to the number of workers results in idle workers. Similarly to the sharded case, `multigets` of size 9 reach the network bandwidth with 11.5MB of data per second written to the network by servers. Hence increasing the client count would not result in higher throughputs.

The same increasing trend in average response times is visible for this configuration. This is caused for the same reasons as for sharded `multigets`.

5.3 Histogram

All histograms displayed in this section are the result of unweighted averages across all client instances / middleware hosts. Hence the histogram of response times given by some memtier instance has the same weight than any other memtier instance, irrespective of the actual throughput measured by said instance. This results in small inaccuracies in the data as memtier

instances with smaller throughput should have a smaller impact on the histogram than other memtier instances.

5.3.1 Sharded Case

Figure 36 illustrates the response time histogram of sharded `multigets` as measured by the clients. Each bucket represents the percentage of total requests having a response time higher or equal to the bucket in question, yet lower than the next bucket. The first and last buckets represent the percentage of requests having lower and higher response times than the one indicated respectively.

As one can see, the vast majority of requests have a response time between 2.4 and 4.2 milliseconds. Moreover, the histogram shows a single peak in the distribution of response times. The reason for the very high percentage for the last bucket is only due to the grouping of all requests having response times higher than 6.9 milliseconds. The actual distribution decreases gradually until reaching zero.
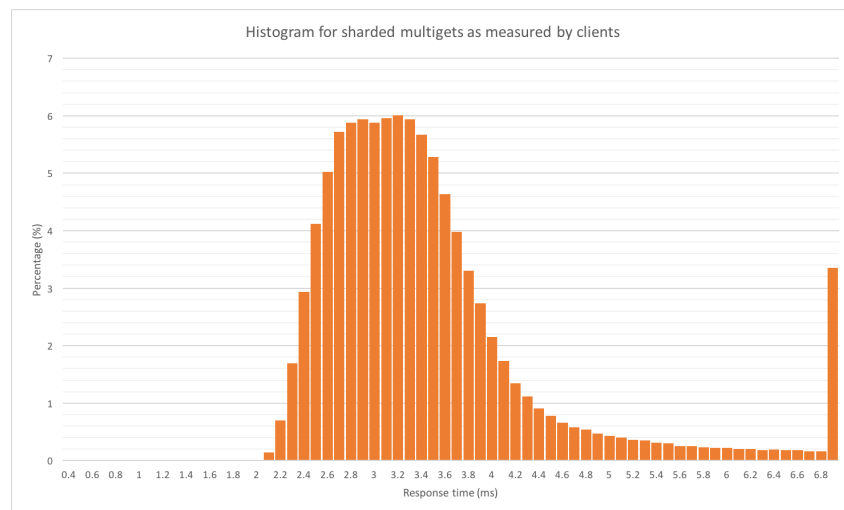
Figure 36: Histogram of response times for sharded `multigets` based on client data

Figure 37 represents the same data but measured on the middleware. As one can see, the overall response times are lower and more concentrated around the peak. The overall lower times are due to the fact that the time spent in network between clients and middlewares is not included in response time measurements for the middleware. The reason for more concentrated response times is the lack of network latency volatilities between clients and middlewares. These are random and add some spread to the response times observed by the clients.

5.3.2 Non-Sharded Case

Figure 38 shows the response times measured by clients for non-sharded `multigets`. As once can see, the overall spread of response times is much larger than for the sharded case. The vast majority of requests are amassed around two peaks. The second peak is comparable to the one seen in figure 36 (if not as high) whereas the first peak has much lower response times. This is caused by network latencies being much lower for one server (namely "`server1`"[19]).

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[19]`logs/get_and_multigets(2017-11-18_13h10)/mw_._ping.log`
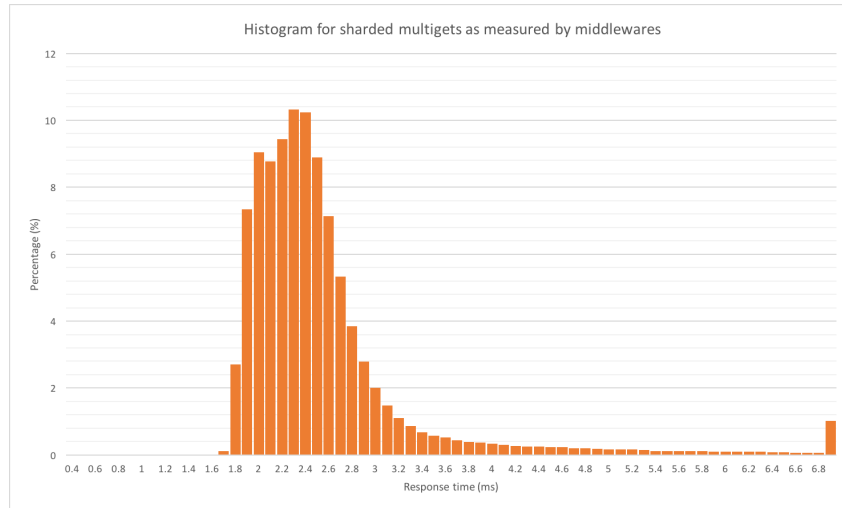
Figure 37: Histogram of response times for sharded `multigets` based on middleware data

In the sharded case, this did not impact service rates of the middleware as the middleware had to wait for all servers to respond. Hence the slowest servers ("`server2`" and "`server3`") dictated the server time (here slow server means servers with high response times, even if due to network latencies). However, in the non-sharded case, about one third of all requests (due to load balancing) are sent to the server having lower network latencies, hence resulting in lower overall response times for this subset of requests. Because of this distribution of requests, one can also see that the first peak is smaller than the second one.
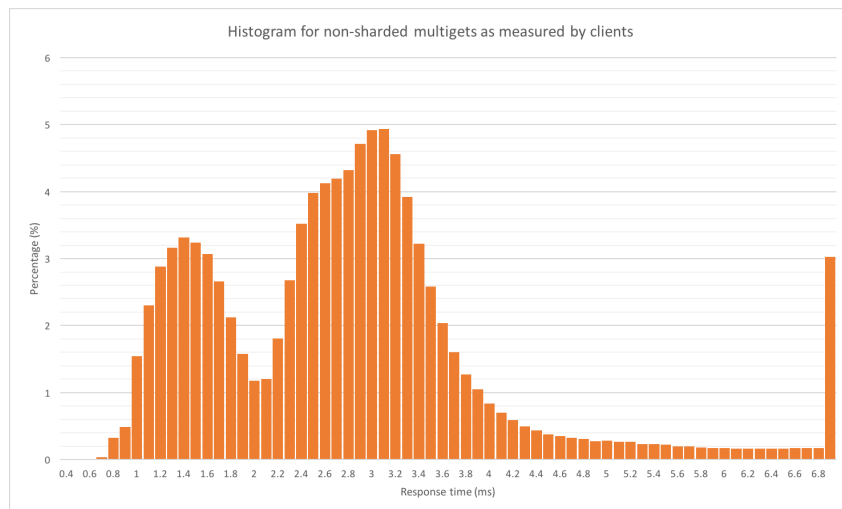
Figure 38: Histogram of response times for non-sharded `multigets` based on client data

As seen in figure 39, the data collected on the middleware reflect the same as the clients. Moreover, the overall response times are again slightly lower than for clients and concentrated around the two peaks. This follows for the same reasons as for the sharded case.
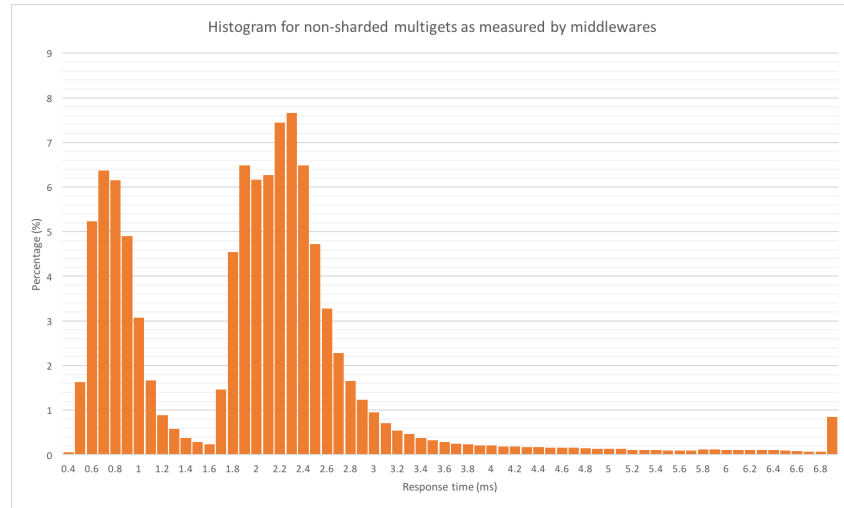
Figure 39: Histogram of response times for non-sharded `multigets` based on middleware data

5.4 Summary

In general, non-sharded `multigets` are preferred over sharded ones. This is due to the fact that sharded requests cannot take advantage of the situation where a server or subset of servers behaves better than the rest. Therefore, non-sharded `multigets` have a lower average response time than sharded ones. However, due to the potentially large discrepancy between server behaviours, non-sharded requests are not very consistent in terms of response times. This is seen in figure 35, where the difference in response times between 25th, 50th, and 75th percentiles is much larger than in the sharded case. Nonetheless, as speed and throughput are usually the primary goals of such systems, non-sharded requests are superior, even if they offer less consistency than sharded requests.

6 2K Analysis

The experiments conducted in this section are 6 different $2^k \cdot r$ experiments with three factors ($k = 3$) and three repetitions ($r = 3$). For three different types of workload (read-only, write-only, and read-write (balanced 1:1 ratio)), the modified factors are:

1. the number of servers used as backends (2 or 3), denoted A;

2. the number of middlewares used (1 or 2), denoted B;

3. the number of worker thread used per middleware (8 or 32), denoted C.

Each of these configurations are then analysed for throughput and response time. Moreover, notice that all measurements will be taken from the middleware(s). This has the objective to reduce inaccuracies in variation measurements due to network latencies between clients and middlewares.

The following variables are defined:

$$x_A = \begin{cases} -1 & \text{if 2 servers are used} \\ 1 & \text{if 3 servers are used} \end{cases} \tag{1}$$

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

$$x_C = \begin{cases} -1 & \text{if 8 workers are used} \\ 1 & \text{if 32 workers are used} \end{cases} \tag{3}$$

The model used is multiplicative as every middleware has a number of workers and each of these workers is connected to all servers. Therefore, the data in the following tables under the headings "Repetitions" is actually the **logarithm** of throughput or response time. All other computations within the tables is then based on that data.

6.1 Read-Only Workload

Table 6 illustrates the impact on throughput of changing the factors. The last row in this table gives the portion of the variation affected by the change in the given factor.

From the last row in said table, one can see that the only factors affecting throughput are the number of middlewares and the number of workers. The number of workers has a slightly bigger impact, as the actual change in number of workers quadruples when going from 8 to 32 workers, whereas only doubles by adding a second middleware. However, note that the effect of increasing workers is only slightly better than the effect of adding a middleware. Therefore, it is preferred to increase from one middleware to two rather than doubling the number of workers on a single middleware.

All cross-effects between variables are insignificant, not even reaching one percent in any of the cases.

As expected, the results observed in table 7 show the same behaviour to the previous table mapped to response time. However, impacts have grown in importance. This entire shift in the significance of the factors is caused by the network latencies between middleware and clients

Configuration								Repetitions			Statistics			
I	A	B	C	AB	AC	BC	ABC	1	2	3	mean	error 1	error 2	error 3
1	1	1	1	1	1	1	1	4.338152331	4.341791014	4.351575288	4.343839544	-0.005687213	-0.00204853	0.007735743
1	1	1	-1	1	-1	-1	-1	3.974227789	3.967104915	3.973830703	3.971721136	0.002506653	-0.004616221	0.002109567
1	1	-1	1	-1	1	-1	-1	4.03632692	4.035952778	4.034917589	4.035732429	0.000594491	0.000220349	-0.00081484
1	1	-1	-1	-1	-1	1	1	3.619358159	3.619262944	3.624463873	3.621028325	-0.001670166	-0.001765382	0.003435548
1	-1	1	1	-1	-1	1	-1	4.347825024	4.350403338	4.350422961	4.349550441	-0.001725417	0.000852897	0.00087252
1	-1	1	-1	-1	1	-1	1	4.022168459	4.030861717	4.034256862	4.029095679	-0.00692722	0.001766038	0.005161182
1	-1	-1	1	1	-1	-1	1	4.045849877	4.051759146	4.042921865	4.046843629	-0.000993752	0.004915517	-0.003921764
1	-1	-1	-1	1	1	1	-1	3.686242903	3.685602921	3.689396553	3.687080792	-0.00083789	-0.001477871	0.002315761
Aggregates														
32.08489198	-0.140249107	1.303521624	1.467040111	0.014078227	0.106604914	-0.08189377	-0.00327762	Total					SST	SSE
4.010611497	-0.017531138	0.162940203	0.183380014	0.001759778	0.013325614	-0.010236721	-0.000409702	Total/8					1.458775161	0.000278188
	0.505641976	43.67967397	55.32569577	0.005094937	0.292144257	0.172402927	0.00027616	Percentage impact						

Table 6: Read-only 2^kr analysis for throughput

Configuration								Repetitions			Statistics			
I	A	B	C	AB	AC	BC	ABC	1	2	3	mean	error 1	error 2	error 3
1	1	1	1	1	1	1	1	0.826011299	0.82045359	0.805116722	0.81719387	0.008817429	0.00325972	-0.012077148
1	1	1	-1	1	-1	-1	-1	1.287864319	1.29415737	1.287244059	1.28975525	-0.001890931	0.004402121	-0.00251119
1	1	-1	1	-1	1	-1	-1	1.187524257	1.188001791	1.187870768	1.187798939	-0.000274682	0.000202853	7.18296E-05
1	1	-1	-1	-1	-1	1	1	1.648799585	1.649266261	1.644363093	1.647476313	0.001323272	0.001789948	-0.00311322
1	-1	1	1	-1	-1	1	-1	0.806318625	0.820689889	0.808797077	0.811935197	-0.005616572	0.008754692	-0.00313812
1	-1	1	-1	-1	1	-1	1	1.236231432	1.227235028	1.223332742	1.228933067	0.007298365	-0.001698039	-0.005600325
1	-1	-1	1	1	-1	-1	1	1.171455198	1.164427122	1.173661728	1.169848016	0.001607182	-0.005420894	0.003813712
1	-1	-1	-1	1	1	1	-1	1.579507473	1.581580792	1.577908109	1.579665458	-0.000157985	0.001915334	-0.001757349
Aggregates														
9.73260611	0.151842633	-1.436971342	-1.759054066	-0.019680922	-0.105423442	-0.020064433	-0.005703578	Total					SST	SSE
1.216575764	0.018980329	-0.179621418	-0.219881758	-0.002460115	-0.01317793	-0.002508054	-0.000712947	Total/8					1.948343575	0.000537106
	0.443765132	39.74311818	59.55580511	0.007455154	0.213914441	0.007748533	0.000626124	Percentage impact						

Table 7: Read-only 2^kr analysis for response time

not being taken into account. As a consequence, the response times used in table 7 are lower than the actual one. Therefore changes in response time caused by the modifications in the configuration feel more significant than when measured by the client.

6.2 Write-Only Workload

Table 8 illustrates the effect of changes in the factors outlined in equation 1, 2 and 3. For write-only workloads, the effects observed are extremely similar to read-only workloads, both for throughput and response time.

6.3 Read-Write Workload

As expected, since the effects were similar to write-only and for read-only workloads, the impact of the factors chosen for this analysis is also the same when using a read-write workload. This can be seen in tables 10 and 11.

6.4 Summary

As seen in tables 6, 7, 8, 9, 10, and 11, the most important factors affecting the performance of the system are the number of workers per middleware and the number of middlewares used. The importance of these factor does not vary significantly between different workloads.

Configuration								Repetitions			Statistics			
I	*A*	*B*	*C*	*AB*	*AC*	*BC*	*ABC*	1	2	3	mean	error 1	error 2	error 3
1	1	1	1	1	1	1	1	4.100565245	4.108614911	4.109351976	4.106177377	-0.005612133	0.002437533	0.003174599
1	1	1	-1	1	-1	-1	-1	3.784667209	3.788414095	3.78358828	3.785556528	-0.000889319	0.002857567	-0.001968248
1	1	-1	1	-1	1	-1	-1	3.80815187	3.801720053	3.808356164	3.806076029	0.002075841	-0.004355976	0.002280135
1	1	-1	-1	-1	-1	1	1	3.423945917	3.418226692	3.415670165	3.419280925	0.004664992	-0.001054232	-0.003610759
1	-1	1	1	-1	-1	1	-1	4.162679013	4.161450361	4.165328921	4.163152765	-0.000473751	-0.001702404	0.002176156
1	-1	1	-1	-1	1	-1	1	3.802315251	3.798190388	3.795133258	3.798546299	0.003768952	-0.000355911	-0.003413041
1	-1	-1	1	1	-1	-1	1	3.858680034	3.88385654	3.883808304	3.875448293	-0.016768259	0.008408247	0.008360011
1	-1	-1	-1	1	1	1	-1	3.448317831	3.445220719	3.450012261	3.44785027	0.000467561	-0.002629552	0.002161991
Aggregates														
30.40208849	-0.167906768	1.304777452	1.499620442	0.02797645	-0.084788535	-0.129165811	-0.003182698	**Total**					**SST**	**SSE**
3.800261061	-0.020988346	0.163097182	0.187452555	0.003497056	-0.010598567	-0.016145726	-0.000397837	**Total/8**					1.502153674	0.000592149
	0.703806555	42.50008412	56.14093056	0.019538991	0.179469712	0.416497172	0.000252876	**Percentage impact**						

Table 8: Write-only 2^kr analysis for throughput

Configuration								Repetitions			Statistics			
I	*A*	*B*	*C*	*AB*	*AC*	*BC*	*ABC*	1	2	3	mean	error 1	error 2	error 3
1	1	1	1	1	1	1	1	1.103271737	1.098848274	1.089784516	1.097301509	0.005970228	0.001546765	-0.007516993
1	1	1	-1	1	-1	-1	-1	1.486449401	1.480127832	1.487654847	1.484744027	0.001705374	-0.004616195	0.00291082
1	1	-1	1	-1	1	-1	-1	1.420646402	1.425229339	1.418471457	1.421449066	-0.000802664	0.003780273	-0.002977609
1	1	-1	-1	-1	-1	1	1	1.8454549	1.852149031	1.854865792	1.850823241	-0.005368341	0.00132579	0.004042551
1	-1	1	1	-1	-1	1	-1	1.042514533	1.046544559	1.047016451	1.045358514	-0.002843981	0.001186045	0.001657937
1	-1	1	-1	-1	1	-1	1	1.4514018	1.470165334	1.472406571	1.464657902	-0.013256101	0.005507433	0.007748669
1	-1	-1	1	1	-1	-1	1	1.370173582	1.346685171	1.346990413	1.354616389	0.015557194	-0.007931218	-0.007625976
1	-1	-1	-1	1	1	1	-1	1.819480188	1.823913089	1.819035236	1.820809504	-0.001329316	0.003103585	-0.001774268
Aggregates														
11.53976015	0.168875534	-1.355636248	-1.702309195	-0.024817294	0.068675812	0.088825385	-0.004962071	**Total**					**SST**	**SSE**
1.442470019	0.021109442	-0.169454531	-0.212788649	-0.003102162	0.008584476	0.011103173	-0.000620259	**Total/8**					1.792368433	0.000853927
	0.596674461	38.44946728	60.62906509	0.012885843	0.098676011	0.165073811	0.000515146	**Percentage impact**						

Table 9: Write-only 2^kr analysis for response time

Configuration								Repetitions			Statistics			
I	A	B	C	AB	AC	BC	ABC	1	2	3	mean	error 1	error 2	error 3
1	1	1	1	1	1	1	1	4.214519993	4.217456635	4.206204336	4.212726988	0.001793004	0.004729647	-0.006522652
1	1	1	-1	1	-1	-1	-1	3.888889628	3.887768461	3.88709099	3.88791636	0.000973268	-0.000147898	-0.00082537
1	1	-1	1	-1	1	-1	-1	3.922951108	3.917921487	3.919346173	3.920072923	0.002878185	-0.002151436	-0.000726749
1	1	-1	-1	-1	-1	1	1	3.532751195	3.533548056	3.531876306	3.532725186	2.60094E-05	0.00082287	-0.000848879
1	-1	1	1	-1	-1	1	-1	4.261166183	4.26102037	4.263555297	4.26191395	-0.000747767	-0.00089358	0.001641347
1	-1	1	-1	-1	1	1	1	3.921279296	3.914645233	3.921422438	3.919115656	0.00216364	-0.004470423	0.002306782
1	-1	-1	1	1	-1	-1	1	3.970864443	3.97004744	3.973773041	3.971561641	-0.000697198	-0.001514201	0.002211399
1	-1	-1	-1	1	1	1	-1	3.57535818	3.57082304	3.576593272	3.574258164	0.001100016	-0.003435124	0.002335108
Aggregates														
31.28029087	-0.173407954	1.28305504	1.452260137	0.012635439	-0.027943406	-0.117042293	-0.008031925	**Total**					**SST**	**SSE**
3.910036358	-0.021675994	0.16038188	0.181532517	0.00157943	-0.003492926	-0.014630287	-0.001003991	**Total/8**					1.425168774	0.00014479
	0.791230457	43.31671796	55.49499322	0.004200932	0.020545828	0.36045463	0.001697479	**Percentage impact**						

Table 10: Read-write 2^kr analysis for throughput

Configuration								Repetitions			Statistics			
I	A	B	C	AB	AC	BC	ABC	1	2	3	mean	error 1	error 2	error 3
1	1	1	1	1	1	1	1	0.976465709	0.97325092	0.980023957	0.976580195	-0.000114487	-0.003329275	0.003443762
1	1	1	-1	1	-1	-1	-1	1.37513759	1.376077722	1.376501701	1.375905671	-0.000768081	0.000172051	0.00059603
1	1	-1	1	-1	1	-1	-1	1.306654261	1.309797488	1.306826462	1.307759404	-0.001105143	0.002038084	-0.000932941
1	1	-1	-1	-1	-1	1	1	1.736233396	1.736097529	1.738027303	1.736786076	-0.00055268	-0.000688547	0.001241227
1	-1	1	1	-1	-1	1	-1	0.929725972	0.92370591	0.930625494	0.928019125	0.001706847	-0.004313215	0.002606368
1	-1	1	-1	-1	1	1	1	1.341156462	1.34644047	1.340120857	1.342572596	-0.001416134	0.003867874	-0.00245174
1	-1	-1	1	1	-1	-1	1	1.254328071	1.256270581	1.252590871	1.254396508	-6.8437E-05	0.001874074	-0.001805637
1	-1	-1	-1	1	1	1	-1	1.692714027	1.697785413	1.691933701	1.694144381	-0.001430353	0.003641033	-0.002210679
Aggregates														
10.61616396	0.177898736	-1.37000878	-1.682653492	-0.014110447	0.025949196	0.054895599	0.004506795	**Total**					**SST**	**SSE**
1.327020495	0.022237342	-0.171251098	-0.210331686	-0.001763806	0.00324365	0.00686195	0.000563349	**Total/8**					1.779036163	0.000110752
	0.667101959	39.56336226	59.6809701	0.004196894	0.014193657	0.063521617	0.000428136	**Percentage impact**						

Table 11: Read-write 2^kr analysis for response time

7   Queuing Models

This section provides an analysis of the system under different queuing models. First, the experimental results on section 4 will be compared to M/M/1 and M/M/m queuing model. Then, section 3 will be used to build a network of queues. In each case, the results of the queuing models will be compared to the results obtained from the tests.

All tables for M/M/1 and M/M/m models are generated with `processing/compute_mm1.py` and `processing/compute_mmn.py` scripts. The data in `processing/final/queuing_model/queuing_model.xlsx` is just a copy of the data from "Throughput of Writes" used as input (hardcoded) for the scripts.

7.1   M/M/1 Model

Figure 40 shows the model used for this subsection. In this case, the system used during section 4 is modelled as a queue with a single entity providing the service (the equivalent of "server" in traditional queuing theory). This differs from the actual system model used during the experiment as two middlewares were used (therefore two separate queues), each having a variable amount of entities providing the service (worker threads). The model is open as the clients are not contained in the model and hence the boundaries of the system are the net-thread for input from outside the system and the worker threads as they send responses back to clients outside the system. However, the memcached servers are considered as being part of the worker threads of the middleware and are thus contained in the model.
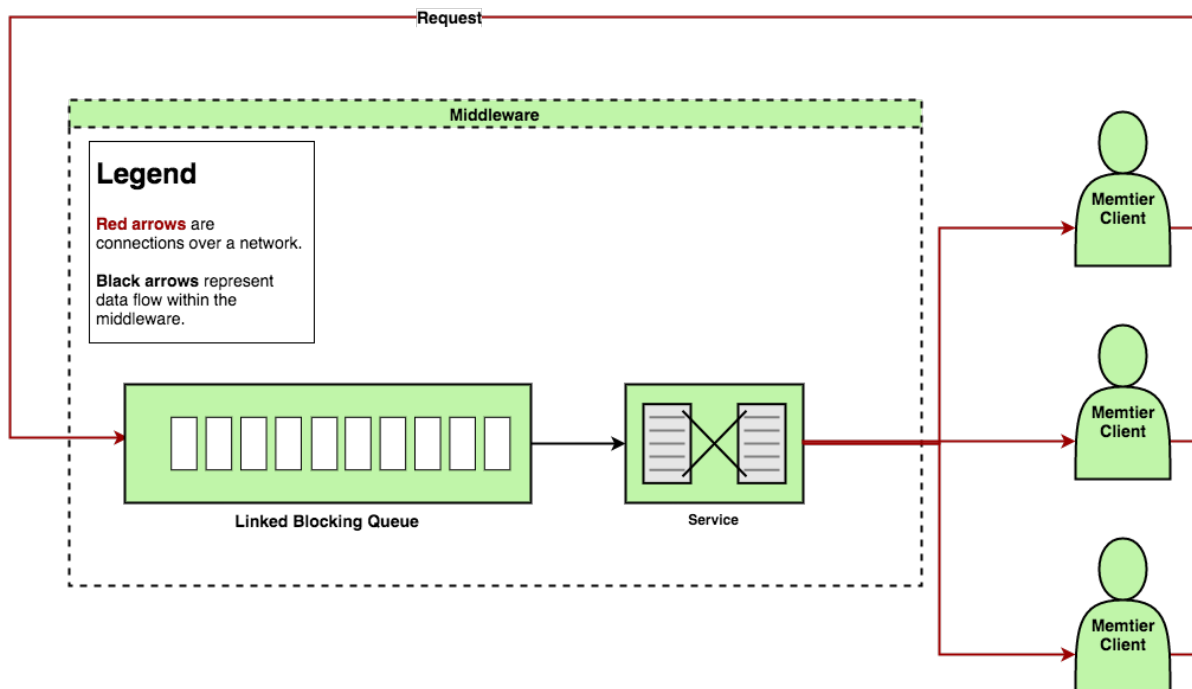

Figure 40: The middlewares modelled as an M/M/1 queue

The input to this model are the following:

1. The *service rate* will be computed from the mean service time at maximum throughput of the middlewares (shown in 5). The service time is computed from the difference between average response time measured on the middlewares and average queuing times (both

8 Workers (16 total)							
Clients	**AR**	**SR**	**ST (ms)**	**Util (%)**	**QL**	**QT (ms)**	**RT (ms)**
2	3714.358	6271.214	0.15946	59.229	0.86042	0.23165	0.39111
4	5998.812	6271.214	0.15946	95.656	21.065	3.5116	3.6711
8	6218.021	6271.214	0.15946	99.152	115.9	18.64	18.8
16	6207.667	6271.214	0.15946	98.987	96.696	15.577	15.736
24	6212.946	6271.214	0.15946	99.071	105.64	17.003	17.162
32	6198.538	6271.214	0.15946	98.841	84.301	13.6	13.76
40	6217.821	6271.214	0.15946	99.149	115.46	18.57	18.729
48	6202.592	6271.214	0.15946	98.906	89.399	14.413	14.573
56	6155.137	6271.214	0.15946	98.149	52.045	8.4556	8.615

Table 12: Data for M/M/1 queuing model for 8 worker configuration

taken at maximum throughput configurations). The inverse of this difference is then taken and multiplied by the total number of worker threads in the system. The result of this is used as the service rate.

2. The throughput as measured by the middleware will be taken as the *arrival rate*.

The reasoning behind the choice of computation of these parameters is rather simple. For the service rate, due to the parallelism introduced by the workers, if a single worker thread were to perform the same work sequentially, it would require that thread to be exactly as many times faster than the average at there are workers in parallel. Hence the service time of this single worker can be computed by dividing the average service time of the parallel workers by the number of parallel workers. This is equivalent to multiplying the average service rate of the parallel workers by the total number of workers. Notice that this is the number of worker across the entire system, i.e. both middlewares. Therefore, in order to compute the service rate used in this subsection for the 8 worker configuration, the average service time measured during the experiment is multiplied by 16.

For the arrival rate, the reasoning is even more simplistic. As all virtual memtier clients will wait for a response from the middlewares before sending another request, it is trivial that the average throughput is equal to the average arrival rate.

Using these parameters, one obtains the data shown in tables 12, 13, 14, and 15. In these tables, **AR** denotes arrival rate, **SR** denotes service rate, **ST** denotes service time, **Util** denotes utilisation, **QL** denotes queue length, **QT** denotes queue time, and **RT** denotes response time.

In table 12, one can clearly see that the highest utilisation is reached with 8 clients per thread. This follows as it is the point of highest throughput found by the middleware. Moreover, nearly full utilisation is reached already at 4 clients per thread. This coincides with the point of saturation found during the analysis in section 4. Queue lengths and therefore also queue time do not coincide at all with data measured by the middleware. This is due to the fact that the client count gives an upper bound to the number of requests in the system. Therefore, at say 8 clients per thread, there is not enough total clients (48) to even generate 115 requests simultaneously.

On the other hand, note that at higher client counts, the queue length is much lower than the ones given by the measurements. This is due the model design. A single worker has a different impact on a queue to 16 workers being 16 times slower.

16 Workers (32 total)							
Clients	AR	SR	ST (ms)	Util (%)	QL	QT (ms)	RT (ms)
2	3621.567	10692.54	0.093523	33.87	0.17347	0.0479	0.14142
4	6814.504	10692.54	0.093523	63.731	1.1199	0.16434	0.25786
8	9249.221	10692.54	0.093523	86.502	5.5433	0.59932	0.69285
16	10412.3	10692.54	0.093523	97.379	36.181	3.4749	3.5684
24	10259.3	10692.54	0.093523	95.948	22.721	2.2147	2.3082
32	10320.58	10692.54	0.093523	96.521	26.781	2.5949	2.6885
40	10164.5	10692.54	0.093523	95.062	18.299	1.8003	1.8938
48	10287.29	10692.54	0.093523	96.21	24.423	2.3741	2.4676
56	10623.76	10692.54	0.093523	99.357	153.46	14.445	14.538

Table 13: Data for M/M/1 queuing model for 16 worker configuration

32 Workers (64 total)							
Clients	AR	SR	ST (ms)	Util (%)	QL	QT (ms)	RT (ms)
2	3725.717	13278.59	0.075309	28.058	0.10943	0.029371	0.10468
4	7082.292	13278.59	0.075309	53.336	0.60963	0.086078	0.16139
8	10030.78	13278.59	0.075309	75.541	2.3331	0.23259	0.3079
16	12332.62	13278.59	0.075309	92.876	12.108	0.98181	1.0571
24	12871.18	13278.59	0.075309	96.932	30.624	2.3792	2.4545
32	12993.27	13278.59	0.075309	97.851	44.561	3.4296	3.5049
40	13032.93	13278.59	0.075309	98.15	52.072	3.9954	4.0707
48	13175.4	13278.59	0.075309	99.223	126.69	9.6159	9.6912
56	12834.42	13278.59	0.075309	96.655	27.929	2.1761	2.2514

Table 14: Data for M/M/1 queuing model for 32 worker configuration

As queue length impacts queue time, the queue times computed by the model do not match response times measured during the experiment. Similarly, as queue time impacts response time, the response times are very different to the measurements as well.

Table 13 illustrates the data obtained when applying the M/M/1 model to the system running two middlewares with 16 worker threads as a configuration. Once more, the system reaches near full utilisation at the same point saturation was observed during the experiment. Notice that this time queue lengths and queue times are reasonably accurate before the point of saturation. However, past that point they no longer match data gathered during the experiment.

Moreover, small changes in the utilisation result in very large changes in queue lengths when utilisation is close to 100%. This is again due to the design of this model. As the model assumes only one very fast worker, reaching high utilisations has much more impact on the queue than when modelling with more workers.

Table 14 shows utilisation levels above 90% for 16 clients per thread and above. This is also the point of saturation observed during experiments. For the rest of the data, the same analysis as given for 16 workers can be applied here.

The data illustrated in table 15 shows the M/M/1 model applied to the system with a configuration of 64 workers per middleware. As close to full utilisation is reached much later, queue lengths computed here are much more accurate. However, response times are not accurate

64 Workers (128 total)							
Clients	AR	SR	ST (ms)	Util (%)	QL	QT (ms)	RT (ms)
2	3712.546	15590.7	0.064141	23.813	0.074427	0.020047	0.084188
4	7000.029	15590.7	0.064141	44.899	0.36585	0.052265	0.11641
8	9851.5	15590.7	0.064141	63.188	1.0846	0.1101	0.17424
16	12849.02	15590.7	0.064141	82.415	3.8624	0.3006	0.36474
24	13445.12	15590.7	0.064141	86.238	5.4041	0.40194	0.46608
32	13990.43	15590.7	0.064141	89.736	7.8452	0.56076	0.6249
40	14844.52	15590.7	0.064141	95.214	18.942	1.276	1.3402
48	15243.51	15590.7	0.064141	97.773	42.929	2.8162	2.8803
56	15421.14	15590.7	0.064141	98.912	89.96	5.8335	5.8977

Table 15: Data for M/M/1 queuing model for 64 worker configuration

at all. This is caused by the fact that service times are much higher than used in the model. In fact, the real average service rate is nearly three milliseconds longer than the response time given in the last row of table 15.
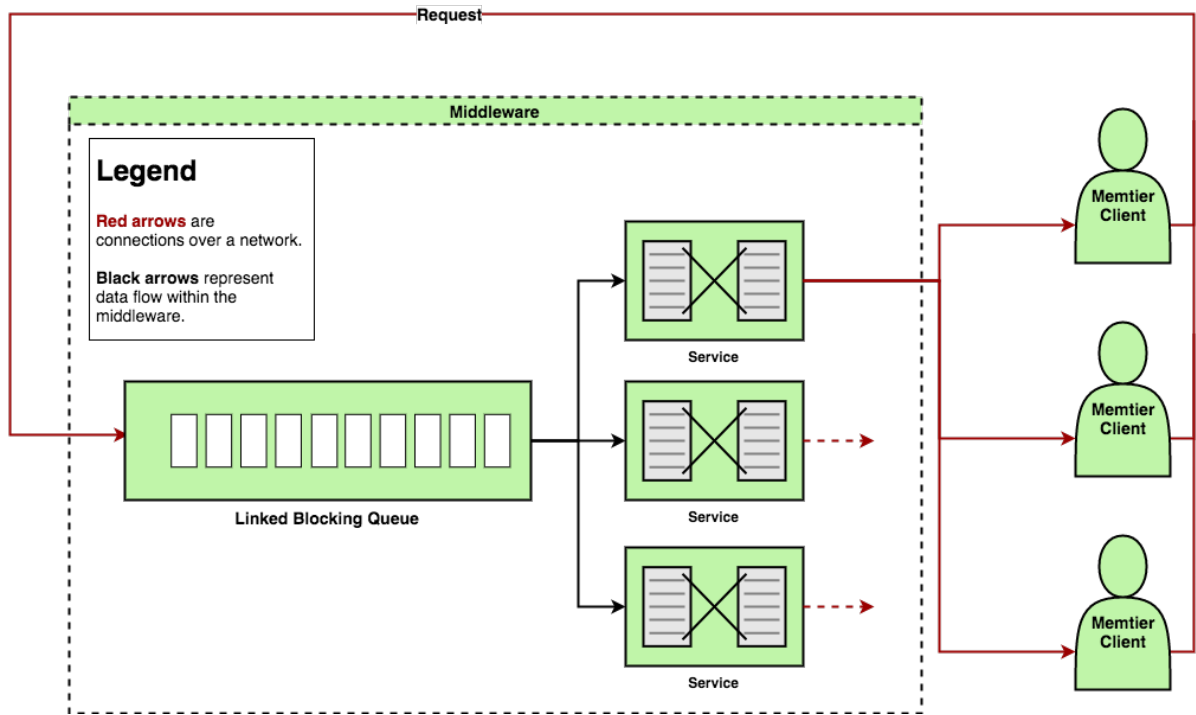
7.2 M/M/m Model

Figure 41: The middlewares modelled as an M/M/m queue

Figure 41 illustrates the model used in this subsection. A variable amount of services are run in parallel. These services are the worker threads and their number is defined by the middleware configuration used. Note that a single queue is still used instead of two distinct ones as in the real system (one for each middleware). The input to this model are the following:

1. The *service rate* is computed from the mean service time at maximum throughput of the

8 Workers (16 total)							
Clients	AR	SR	ST (ms)	Util (%)	QL	QT (ms)	RT (ms)
2	3714.358	391.9509	2.5513	59.229	0.054926	0.014787	2.5661
4	5998.812	391.9509	2.5513	95.656	17.778	2.9636	5.5149
8	6218.021	391.9509	2.5513	99.152	112.28	18.058	20.609
16	6207.667	391.9509	2.5513	98.987	93.091	14.996	17.548
24	6212.946	391.9509	2.5513	99.071	102.02	16.421	18.972
32	6198.538	391.9509	2.5513	98.841	80.71	13.021	15.572
40	6217.821	391.9509	2.5513	99.149	111.84	17.987	20.539
48	6202.592	391.9509	2.5513	98.906	85.802	13.833	16.385
56	6155.137	391.9509	2.5513	98.149	48.521	7.883	10.434

Table 16: Data for M/M/16 queuing model for 8 worker configuration

middlewares. The average service time is computed as for the M/M/1 model. Then its inverse is taken as the service rate.

2. The *arrival rate* is computed as for the M/M/1 model.

The server count (m) used for the model is equal to twice the number of worker threads used in the configurations. This follows from the way the service rate was computed. As the service rate taken from the average service times of a worker, the total number of workers in the system (twice the number given in the configuration as two middlewares are used) serves as the count of service providing entities for the model.

Moreover, the boundaries of the model are exactly the same as for the M/M/1 model. The system is also open.

Table 16 shows the data for a M/M/16 model based on arrival rates and service rates computed from the data measured at maximum throughput for this configuration. Notice that utilisation computed using this model is exactly equal to utilisations computed by the M/M/1 models (see figure 12). This immediately follows from the way service rates were computed.

Moreover, notice that response times no longer approach zero as clients decrease. This is caused as the service time provides a lower bound and M/M/m models provide more realistic approximations of service times. However, generally speaking, this does not results in accurate response times, queue length, or queue times. The actual service time increases as more load is put onto the system. Therefore, the constant service time cannot provide a realistic enough model to accurately approximate response times and queue lengths. On the other hand, as the service time for 8 workers is the most stable one, response times for low load configurations given by the model are actually relatively close to the real values. This is no longer observable for configurations with more workers as service rates vary greatly as more load is added.

The data displayed in table 17 can be analysed in a very similar fashion to the M/M/16 model above. As previously said, response times for low loads are no longer accurate. The instability in service rates is nearly exclusively due to increases in server times for more load. As more load is available due to higher client counts and more worker threads running in parallel, requests stagnate in the memcached servers, making server times longer for the middleware. As these server times are included in the service time, the latter also increase. Therefore, response times for low loads can actually much shorter than the service times given at highest throughput setups.

16 Workers (32 total)						
Clients	AR	SR	ST (ms)	Util (%)	QL	QT (ms)	RT (ms)
2	3621.567	334.1419	2.9927	33.87	7.5977e-08	2.0979e-08	2.9927
4	6814.504	334.1419	2.9927	63.731	0.020496	0.0030077	2.9957
8	9249.221	334.1419	2.9927	86.502	2.1091	0.22803	3.2208
16	10412.3	334.1419	2.9927	97.379	30.912	2.9688	5.9615
24	10259.3	334.1419	2.9927	95.948	17.717	1.7269	4.7197
32	10320.58	334.1419	2.9927	96.521	21.672	2.0999	5.0926
40	10164.5	334.1419	2.9927	95.062	13.456	1.3238	4.3166
48	10287.29	334.1419	2.9927	96.21	19.371	1.883	4.8757
56	10623.76	334.1419	2.9927	99.357	147.81	13.913	16.906

Table 17: Data for M/M/32 queuing model for 16 worker configuration

32 Workers (64 total)						
Clients	AR	SR	ST (ms)	Util (%)	QL	QT (ms)	RT (ms)
2	3725.717	207.4779	4.8198	28.058	1.2683e-17	3.404e-18	4.8198
4	7082.292	207.4779	4.8198	53.336	3.8535e-06	5.4411e-07	4.8198
8	10030.78	207.4779	4.8198	75.541	0.063017	0.0062823	4.8261
16	12332.62	207.4779	4.8198	92.876	5.9315	0.48096	5.3008
24	12871.18	207.4779	4.8198	96.932	23.068	1.7922	6.612
32	12993.27	207.4779	4.8198	97.851	36.671	2.8223	7.6421
40	13032.93	207.4779	4.8198	98.15	44.07	3.3814	8.2012
48	13175.4	207.4779	4.8198	99.223	118.29	8.9779	13.798
56	12834.42	207.4779	4.8198	96.655	20.473	1.5951	6.4149

Table 18: Data for M/M/64 queuing model for 32 worker configuration

64 Workers (128 total)							
Clients	AR	SR	ST (ms)	Util (%)	QL	QT (ms)	RT (ms)
2	3712.546	121.8023	8.21	23.813	5.5415e-40	1.4926e-40	8.21
4	7000.029	121.8023	8.21	44.899	6.8162e-16	9.7374e-17	8.21
8	9851.5	121.8023	8.21	63.188	1.4478e-06	1.4696e-07	8.21
16	12849.02	121.8023	8.21	82.415	0.099012	0.0077058	8.2177
24	13445.12	121.8023	8.21	86.238	0.41633	0.030965	8.241
32	13990.43	121.8023	8.21	89.736	1.3906	0.099393	8.3094
40	14844.52	121.8023	8.21	95.214	9.4545	0.6369	8.8469
48	15243.51	121.8023	8.21	97.773	31.719	2.0808	10.291
56	15421.14	121.8023	8.21	98.912	77.925	5.0531	13.263

Table 19: Data for M/M/128 queuing model for 64 worker configuration

Table 18 shows the same issues as the two before. The response time computed by the model is too low until 16 clients per thread and then it does not increase enough compared to the real values.

The queue lengths in table 19 are the correct order of magnitude. However, with the exception of the last row of the table, queue length still have a significant error (easily reaching over 100% deviations to the real values).

7.3   Network of Queues

Figure 42 shows the system from section 3 with a single middleware. The queue considered in the middleware is the same as for the M/M/m models. However, note that each client instance and instance of memcached also has a queue. The queue for memecached models the internal queue used by memcached. In the specifications of memcached, one can read that when launching with a single thread (as performed during the experiments), memcached uses a listener thread to listen to requests and stores to a queue. The single worker thread then processes requests on the queue.

The motivation behind the queue used for the memtier instances is very similar. As numerous worker threads are used in the middleware, memtier can receive more than two responses simultaneously. However, because at most two threads are used in memtier, not all responses can be handled immediately. Hence creating a queueing situation.

Figure 43 shows the same model but with two separate middlewares.

The data flow represented in these schemas is not accurate as no flow leads back from the servers to the middleware. As the model does not consider any queue when data is passed back from the servers to the middleware, the flow is represented as going directly from the server to the clients.

7.3.1   Single Middleware

First, note that the system is closed. No data is passed out of the system, and no data arrives from the outside. Hence the system contains all devices used in the experiments. Therefore the boundaries of the system are between the testing environment and the outside world.

Second, the number of requests per job is exactly one in each device. This would be different
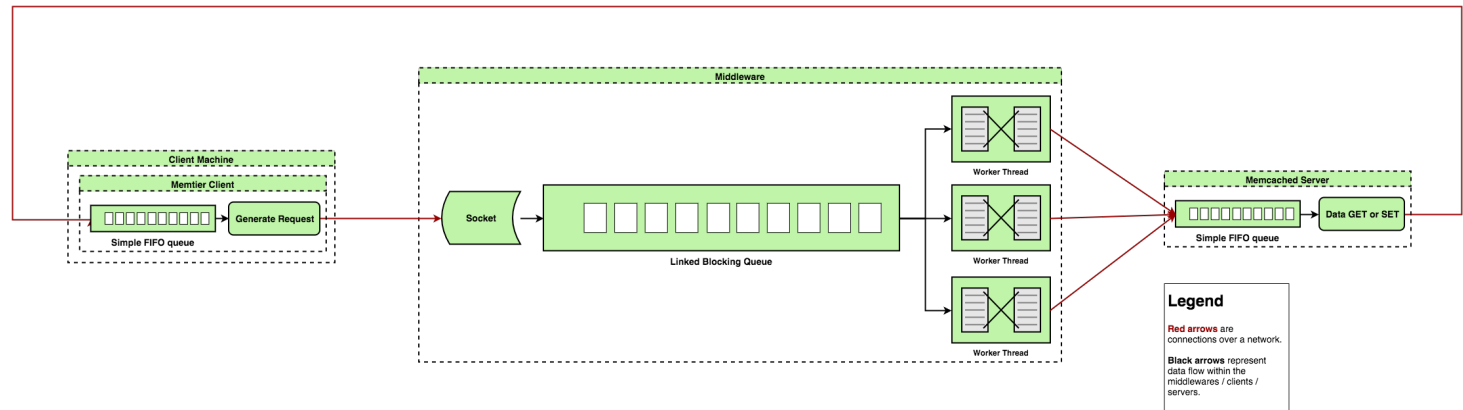
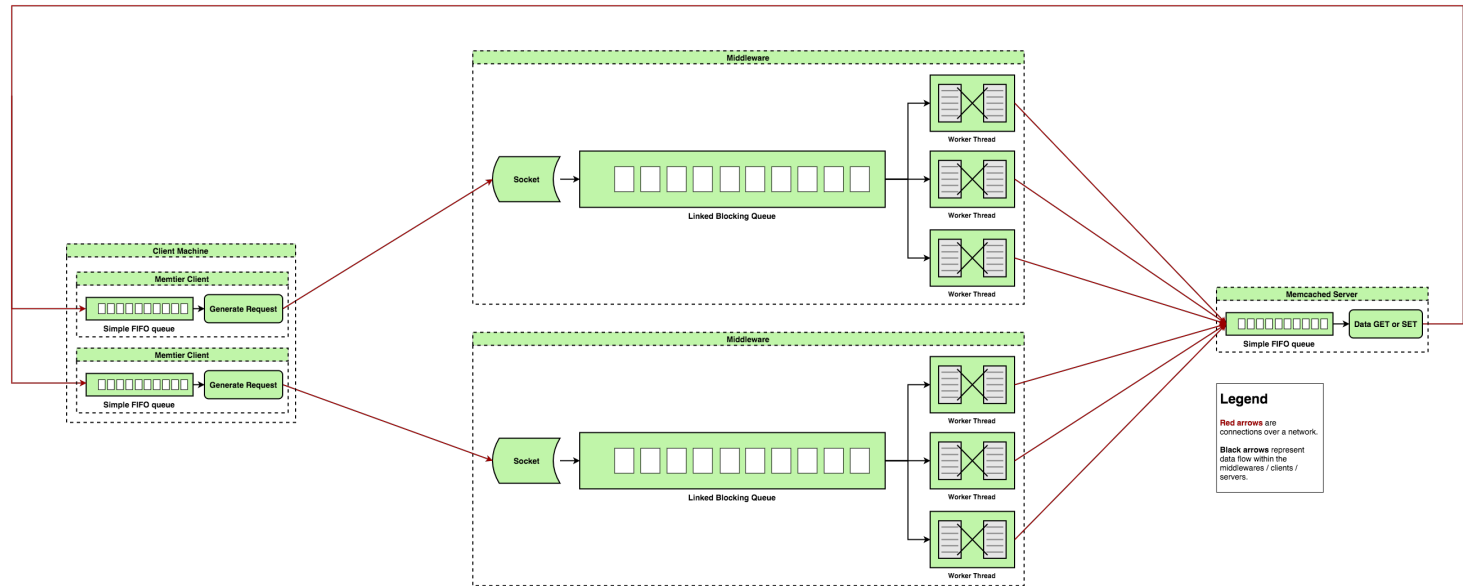Figure 42: System modelled as a network of queues for a single middleware

Figure 43: System modelled as a network of queues for two middlewares

for gets and non-sharded multigets when using several backend servers. However, as only a single memcached server is used, each job spawns only a single request across all devices (not components) in the entire system.

Third, as all but the middleware use a M/M/1 model and the data flow as no fork between individual queuing models, the visit count for each component is exactly one. The only exception are the workers in the middleware, where the average visit count is one over the number of workers used in the middleware device.

Fourth, the total throughput of the system is taken as the average throughput as measured by the client. As no jobs are lost, no jobs are received from outside the system, and no jobs are sent outside the system, the average throughput as measured by the client can also be used as the average arrival rate for each device. Moreover, note that due to the behaviour of memtier, the total number of jobs in the system at any time is equal to the total number of clients.

Finally, in order to compute properties of individual devices in the system, their respective response time will be used. As memtier does not involve any think time, one can assume that the cycle time across the system is the response time as measured by the clients. Then, by the forced flow law, the sum of individual response times from each device is equal to the response time measured by the client. Furthermore, the response time for the backend server is known as it is measured as the server time by the middleware. Moreover, the time a requests spends in the middleware is known as it can be computed by the time between reception of a request from a client and the time the request is completed. As the server is considered a separate device in this model, the server time can be deducted from this time interval to compute the time spend either in queue or processing in a worker within the middleware. The resulting time give the response time of the middleware. Thus, by the forced flow law, the response time of the client machine can be computed by subtracting the middleware's and the server's response times from the system response time.

The service time of the middleware can be observed from the measured timestamps. This usually varies between 0.032 and 0.047 milliseconds[20], depending on load. In the case of the server and the client, service times can be computed the following way:

$$E[r] = \frac{1/\mu}{1 - \rho} \tag{4}$$

$$E[r] \cdot \mu = \frac{1}{1 - \rho} \tag{5}$$

$$\frac{1}{E[r] \cdot \mu} = 1 - \rho \tag{6}$$

$$\frac{1}{E[r] \cdot \mu} = 1 - \frac{\lambda}{\mu} \tag{7}$$

$$\frac{\lambda}{\mu} = 1 - \frac{1}{E[r] \cdot \mu} \tag{8}$$

$$\lambda = \mu - \frac{1}{E[r]} \tag{9}$$

$$\mu = \lambda + \frac{1}{E[r]} \tag{10}$$

$$\frac{1}{S} = \lambda + \frac{1}{E[r]} \tag{11}$$

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[20]`processing/final/queuing_model/network.xlsx`

$$S = \frac{1}{\lambda + \frac{1}{E[r]}} \tag{12}$$

where S is the service time, $E[r]$ the expected response time, λ the arrival rate, and μ the service rate.

Obviously, this does not account for any network latencies between passing from one device to another. However, as the baselines for the performance of both clients and servers have been measured in a previous section, one can tell whether the performance is bound by the network or a client/server device.

Using the service time as explained above, the utilisation law can be used in order to compute utilisation of devices. Moreover, Little's law allows to compute the mean number of jobs in each device. This permits to model the middleware's queuing lengths.

Queue lengths Using Little's law, the queue times in the middleware can be computed. This is achieved by taking the average time spent in the middleware (without server time) and multiplying it by the system throughput. The reason the system throughput can be used is because the average visit count of a job in the middleware is exactly one. This gives very good approximations of the middleware's queue lengths[21]. Note this computation does not take into account that workers may be processing requests, hence removing them from the queue. The reason this is not considered is due to the fact that close to the entirety of a workers processing time is taken up by server times, during which, according to the model, the request is not in the middleware anymore.

Worker utilisation The average visit count for a single worker is one over the total number of workers used in the middleware. Hence, using the forced flow law, one can compute the service demand and utilisation of the workers. This reaches a maximum at 8 workers, eighty total clients, and get operations with only 3.07 percent utilisation[21]. However, note that as the model does not account for the fact that workers have to wait for the servers response to process another request, this is not very accurate. In fact, the workers perform nearly no work, but are busy the entire time, waiting for a server's response. The worker utilisation computed by this model is rather an approximation of the percentage time the workers require CPU resources.

Memcached server Using equation 12, the service time of the server can be computed, hence allowing to also compute its utilisation. Figures 44 and 45 show the computed utilisation based on total client count for all worker configurations. One can clearly observe that utilisation reaches very high levels as the system saturates. However, the baselines without the middleware showed that higher levels of throughput were possible for a single memcached server. Therefore, the high utilisation shown on the graphs is a result of network latencies. These latencies are not considered in the model design but are included in the server's response time. The reason these latencies create problems is that the network can handle much data in parallel, but has a rather long service time (latency from sending data from one point to another). This results in the network severely restricting the system as, in the real system, these times also bound the workers service times.

Memtier client Using the same equation as for the server, one can compute the utilisation of clients. Figures 46 and 47 show the utilisation of clients. Clients also reach very high utilisation levels. However, similarly to memcached, the baselines at the beginning of this report clearly
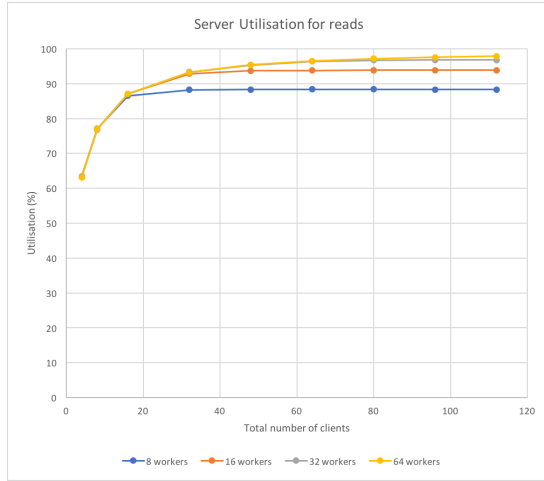
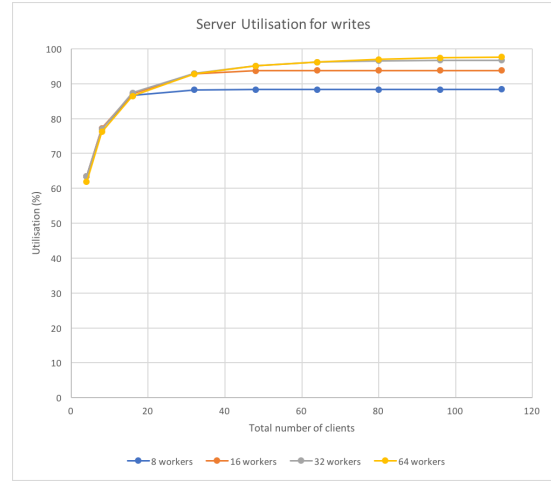Figure 44: Memcached server utilisation for reads

Figure 45: Memcached server utilisation for writes

show that clients can handle much more requests per seconds than the number of jobs in the system during these experiments. Again, network latencies are included in the utilisation computation as they are included in the response time computed for clients. Therefore, network latencies create these high levels of utilisation. As long as the network bandwidth is not reached, the network can actually handle more requests in parallel. However, it creates a bound on response time, hence making the system slow.

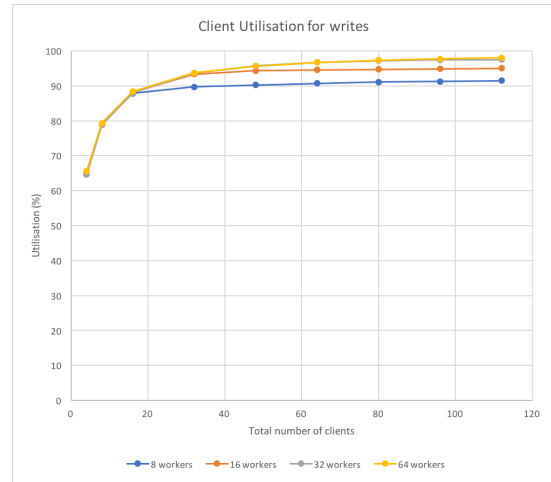Figure 46: Memtier client utilisation for reads

Figure 47: Memtier client utilisation for writes

Summary   There is no significant difference in utilisation between the client and the server. The service times computed using equation 12 are nearly equal for the client and the server. Moreover, their visit count is exactly one hence resulting in very similar service demand. This indicates that they present a comparable bottleneck (using bottleneck analysis as service demand is proportional to utilisation). This implies that the overall bottleneck in this system is the network. However, note that the network can actually handle more requests for low worker configurations as the bandwidth is not yet attained. In such cases, the workers count is actually

Clients	Queue Length Measured	Queue Length computed
4	0.083333333	0.124644061
8	0.214583333	0.313031324
16	0.514583333	0.683040185
32	2.9875	2.984606201
48	9.329166667	9.740633864
64	17.5375	17.49674752
80	24.92291667	25.46997539
96	33.11666667	33.39988338
112	40.24583333	41.34618177

Table 20: Queue length model comparison for 8 worker configuration

Source: `processing/final/queuing_model/network.xlsx`

the bottleneck, as increasing they number allows for more parallelism and more data being sent over the network with the same latency.

7.3.2 Two Middlewares

Just as for the single middleware model, the system under consideration is closed. On top of that, the models boundaries remain unchanged. However, in contrast to the model above, the visit count in each device is no longer one. In the case of the clients and the middlewares, the client count is one half. Therefore, even though the computations for measurements are performed very similarly for this model compared to the one presented above, they are not the same. For example, the average throughput of a single middleware is only half the measured overall throughput from the clients. This follows as throughputs from individual clients were added in post-processing to get the overall throughput of the system.

Server service times and client service times computations can remain unchanged. In the server case this is obvious as the queuing model does not change between single and two middleware models. In the case of clients, half the system's throughput must be taken as the arrival rate as the job visit count for each client instance is only one half.

Queue lengths   Using Little's law the average queue length between the two middlewares can be computed. These estimates are very accurate[21]. Table 20 shows the values for the model compared to the measured values for eight worker read configurations.

Worker utilisation   Worker utilisation is even lower than in the single middleware model. This was to be expected, as throughput does not double but the number of total workers (across both middlewares) doubles. This once again shows that workers do not require a lot of processing power, as they spend most time waiting for server responses.

Memcached server   Figures 48 and 49 show server utilisations for reads and writes respectively. Notice that server utilisations reach higher levels than for the single middleware model. This is caused by an increased load on the server. However, note that, still, lower worker configurations result in lower utilisation. This is caused by the saturation of the middleware

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[21]`processing/final/queuing_model/network.xlsx`

at lower worker counts. In the real system, workers wait for servers to respond, making the workers relatively slow due to large idle waiting times. In these cases, the worker count is the bottleneck and increasing their number reduces this problem. For larger worker counts, the network bandwidth is reached in which case the network becomes the bottleneck.
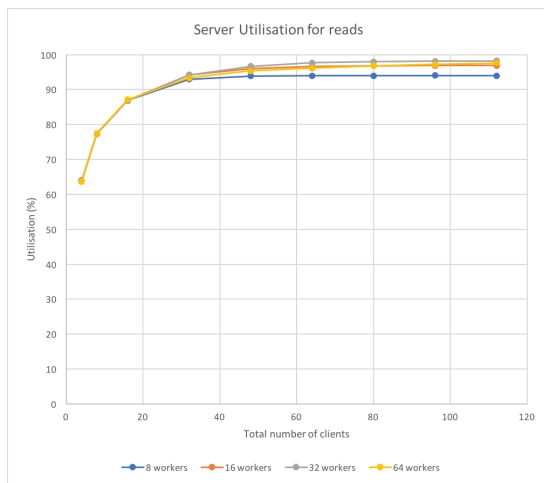

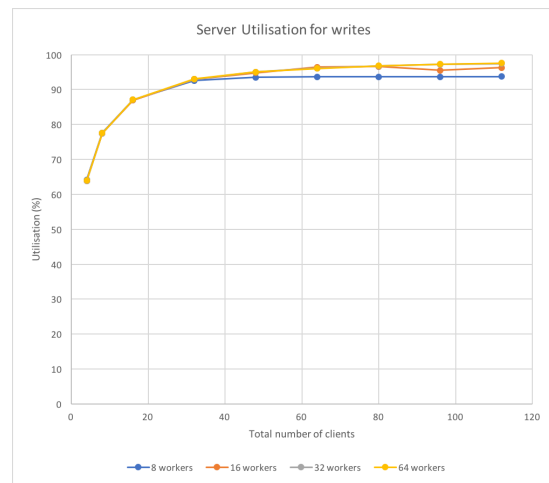Figure 48: Memcached server utilisation for reads

Figure 49: Memcached server utilisation for writes

Memtier clients Client utilisation again is similar to the single middleware model.

7.3.3 Summary

As shown in both network of queues models above, the bottleneck in this system is the network for high worker counts. Sending a large number of requests requires an amount of data to be sent over the network that is larger than the network's bandwidth. At this point, the network becomes a serious bottleneck. However, for lower worker counts, the network bandwidth is not reached. In these cases, the bottleneck of the system is the number of workers used in the system. As these require to wait for servers, which can take relatively long due to network latencies, they become slow and if the parallelism in the middleware is not high enough, this results in a bottleneck. On the other hand, note that reducing the network latencies would make workers much faster, hence reducing their required number to reach a network bandwidth bottleneck. Therefore, improving the network (both lower latencies and higher bandwidths) would drastically increase the overall performance of this system without changing its design.