The Document Title

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1. Abstract
2. Introduction
    - Motivation
    - Current State
    - Prior Work
    - Expectation
3. Object Caches
    - Purpose
    - Desired qualities
    - Design & Implementations
    - Performance measurements and methodology
    - Current State of caches & Usage in industry
4. Testing Methodology
    - Define Quality of Service (99th < 1ms?)
    - What are we interested in (in terms of stats)
    - Testing setup
    - Comparison to testbeds in other papers
    - Memtier & comparison to others
    - Memtier
        - Justify why memtier
        - Outline how memtier works

- Open loop vs closed loop
- Discuss error conditions and repeatability

5. Memcached

   - Outline
     - What memcached is
     - Who/where it is used
     - How would a typical memcached setup look like
     - Link with paper on FB memcached setup and workloads
   - Design decisions
     - Multi-threaded
     - Locks
     - Memory allocation
   - Important configuration options and defaults
   - Memcached Throughput under QoS
     - Latency vs Throughput
     - CPU vs QoS
   - Memcached thread scalability
     -

1 of threads vs QoS

- Thread pinning
- Rx/Tx queues

- Memcached process scalability
  -

2 of processes vs QoS

- Memcached and Group Size
  - based on Where does the time go?

- Summary
    - Maximum throughput under QoS with threads/processes/Rx/Tx configs
    - Cross-link with literature and justify numbers
    - Summarize performance

6. Redis
    - Outline
        - What it is
        - What does it do - feature set
        - Who would/does use it
        - Why would someone choose it over other object caches
        - How does a typical redis deployment look like
    - Redis design
        - Philosophy
            - Simple is better
            - Easier to reason about
        - Single threaded/lock-free
        - Persistence
        - No default sharding
    - Setup and configuration options
    - Benchmarks and results
        - TODO: Similar benchmarks as with memcached
7. Evaluation
    - M vs R in terms of latency under QoS
    - M vs R in terms of throughput under QoS
    - M vs R in terms of total throughput outside QoS (?)

Abstract goes here.. # Motivation

The world is increasingly demanding better and faster access to information. With advances in commodity hardware, and the rise of commodity computing, it has provided means to address one of the ways to increase performance. The proposed ways are as follows - a) Word harder, b) Work smarter and c) Get help, as outlined in [G. Pfsiter, In Search of Clusters]. Commodity computing has been able to address how to get help, namely distribution of work across machines. Caches attempt to address how to work smarter, particularly how to perform less computation.

The increase of distributed computing has also introduced new challenges such as consistency and resiliency of the network under question. The same challenges are having to be addressed across the application stack, including the caching mechanism. With advances in hardware performance and also the size of networks, it will increasingly essential to be able to make caching systems as effective as possible. Inherently, multi-threded and distributed computing poses

With the increased usage of commodity computing [G. Pfister, In Search of Clusters, Prentice Hall PTR, 1998], it has become possible to utilize larger

1. We need to be able to scale on a single server better
2. We need to be able to scale across servers better
3. We need to see if multi-threaded approach is better than single threaded with simpler system # Memory Object Caches

2.1 Purpose

In the traditional sense of way, a cache is a data structure which stores the results of a computation for later retrieval. Generally, a result of a computation is stored against a *key* with a *value* representing the computed result. When retrieving data from the cache, we say there is a *hit* if the key can be found in the cache and a *miss* otherwise. Caching is widely used across the hardware and software stack. For example, modern processors utilize a CPU cache to increase the speed of memory lookup. Similarly, a cache can also be found inside a web server to speed up retrieval of results from the server.

An object cache is a general purpose cache, generally designed as a standalone application, which provides an interface to cache any type of object - for example, an object cache can store large text documents, small tweets or binary data such as images.

A memory object cache is an object with additioanal restriction where data is only stored in the available (or assigned) RAM of the computer. This restriction is important as storing data on hardware slower than RAM would incure too high of a latency and would degrade quality of service.

Both Memcached and Redis are open-source implementations of memory object caches.

2.2 Desired qualities

TODO

2.3 Design & Implementations

TODO

2.4 Performance measurements and methodology

TODO

2.5 Current State of caches & Usage in industry

TODO

3 Methodology

- Quality of Service (99th < 1ms?)
- Testing setup
- Comparison to testbeds in other papers
- Memtier & comparison to others
- Justify Memtier
- Open loop vs closed loop
- What are we interested in
- Discuss error conditions and repeatability

3.1 Quality of Service

Firstly, it is important to define an acceptale quality of service (QoS) for an object cache in question. Distributed systems are increasingly more popular with responses to requests being a composition of smaller responses from respective sub-systems. Given all sub-systems must return a response before the complete response is serviced to the requestor, the slowest of all smaller responses will determine the overall response time. Frequently, the QoS aimed for is sub-1ms latency. Similar target is used by Leverich and Kozyrakis [1]. Therefore, in this study the aim will be to achieve tail latency under 1ms, that is in 99% of cases.

3.2 Testing setup

The performance benchmarks are run on 8 machines with the following configuration: 6 core Intel(R) Xeon(R) CPU E5-2603 v3 @ 1.60GHz [2], 8 GB RAM and 1Gb/s Network Interface Controller (NIC).

All the hosts are connected to a Pica8 P-3297 [3] switch with 48 1Gbps ports with a star as the network topology. A single host is used to run an object cache system while the remaining seven are used to generate workloads against the server.

3.3 Workload generation

Workload for the cache server is generated using Memtier Benchmark [4]. The Memtier Benchmark provides a configurable parallel workload generation for both Memcached and Redis. Additionally, it allows for a high level of configrability.

3.3.1 Memtier Benchmark Behavior

Memtier Benchmark provides various paramters allowing for a variable configuration. As part of the configration, the user is allowed to specify the number of threads and the number of connections per each thread memtier should make. The standard lifecycle of each thread is as follows:

1. Set up n connection configurations
2. For each connection configuration, initiate the connection over the desired protocol (default: TCP)
3. Make a request
4. Tear down the connection
5. Repeat iterations

3.3.2 Open loop vs Closed loop

Memtier is closed loop

- [1] Reconciling High Server Utilization and Sub-millisecond Quality-of-Service
- [2] [Intel(R) Xeon(R) E5-2603](http://ark.intel.com/products/64592/Intel-Xeon-Processor-E5-2603-10M-Cache-1_80-GHz-6_40-GTs-Intel-QPI)
- [3] [Pica8 Datasheet](http://www.pica8.com/wp-content/uploads/2015/09/pica8-datasheet-48x1gbe-p3297.pdf)
- [4] [Memtier Benchmark](https://github.com/RedisLabs/memtier_benchmark)

4 Memcached

4.1 Outline

Memcached is a simple distributed memory object cache [1]. It provides a simple interface to allow systems to store, retrieve and update the contents of the cache. It is developed as an open source project and has been extensively studied in the literature. Often, it is used as an application of choice to benchmark system configurations in terms of network throughput, memory allocation policies and more generally to understand how a system performs under stress. Furthermore, it is often used as an application for experiementation and implementation of next generation technology such as the use of a Field Programmable Gate Array (FPGA) [2].

The API supported by memcached is straightforward. Memcached philosophy is to execute commands against an item of the cache rather than manipulate the cache as a whole. Out of the box, memcached supports the following operations for retrieval: *set, add, replace, append, prepend and cas* [3]. Similarly, memcached supports the following storage commands: *get, gets, delete and incr/decr* [3]. The API is deliberetly designed to be intuitive making the effect of an action predictable. The action labelled *cas* perhaps requires further clarification, however. The full action name is *check and set*, data is stored only if the comparison with current value fails.

Memcached has grown to be a very popular general purpose cache in the industry. Currently, Facebook is considered to have the largest deployment of memcached in production [4] while there are many other companies utilizing large deployments of memcached as building blocks of their infrastructure, these include Twitter[5], Amazon [6] and many others.

In the simplest memcached deployment, an instance of memcached can be run alongside another application, for example a web server. In such a setup, no network communication is required and the web server can talk to memcached over a local unix socket. This configuration has disadvantages, for example, horizontally scaling the web server would require another instance of the cache to be deployed as well potentially leading decreased cache hit rate.

More complicated deployments generally utilize a memcached instance running on a seperate host with all instances of, for example, web servers communicating with a single memcached host. The advantage of such a setup is decreased coupling and increased potential for scalability by adding more instances of both web server and memcached.

In the largest scenarios, such as Facebook, a large number of client applications are talking to a number of memcached clusters responsible for a given type of information. Effectively creating a data layer where any client application can request information from any pool increasing modularity and interoperability of the infrastructure. [Ref?]

(Diagram to illustrate deployments here?)

To illustrate the importance and also the size of a memcached deployment, a workload charasterization from Facebook will be used [7]. Figure below illustrates the throughput observed in a Facebook pools deployed over the course of 7 days. We can observe that the total number of requests is close to 1.26 trillion requests over 7 days, this is on average 2.08 million requests a second. The volume itself is large, however, considering Facebook has 1.44 billion active monthly users [8], however, it does demonstrate the scale at which Facebook utilizes memcached and the impact memcached has on ability to scale and handle traffic at Facebook.

4.2 Design decisions

From the early development stages, memcached has been designed in a client-server architecture. Therefore, a memcached applications receives a command based on its API, executes the command and returns a reply to the client. Memcached is deliberetly designed as a standalone application rather than being integrated into a particular system/framework in order to be able to act as a general purpose

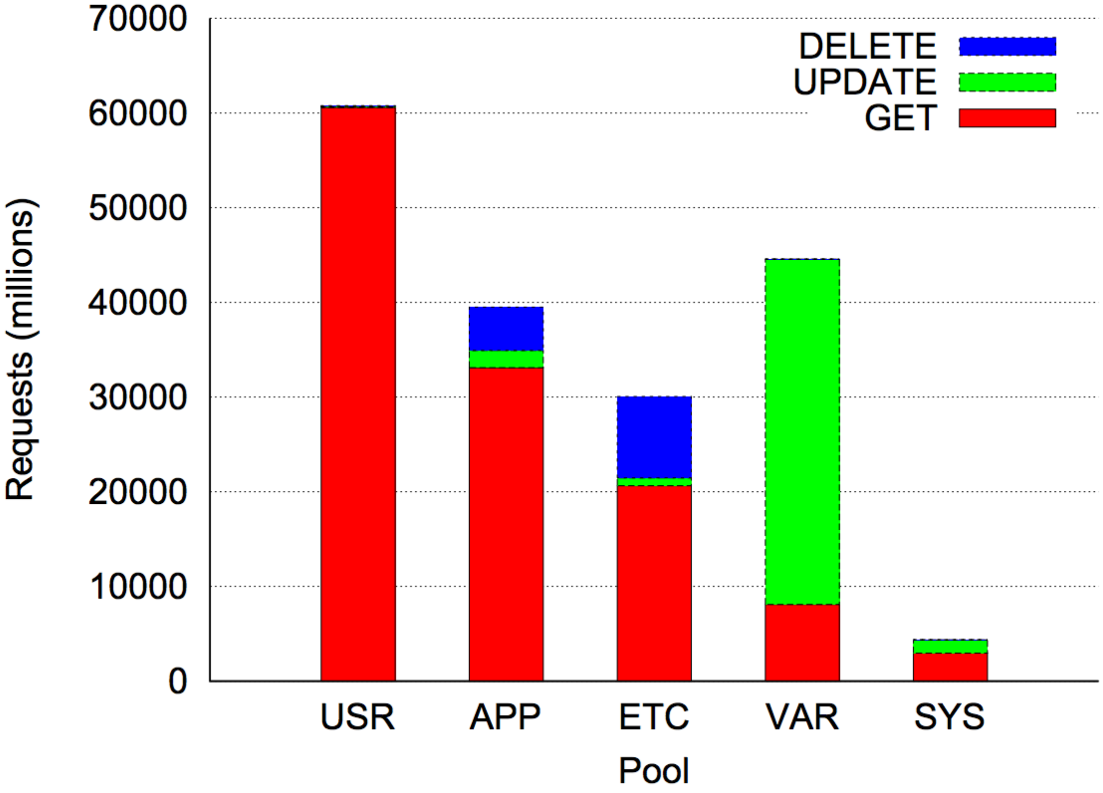


Figure 1: Facebook Pools Operations

cache and allow decoupling of responsibilities in an system architecture.

Memcached implements its distributed protocol through consistent hashing on the client side. Therefore, keeping logic on the server side minimal and allowing the clients to figure out which instance to talk to. In order to further improve horizontal scaling properties of memcached, solutions such as Twemproxy [9] exist to support scalability of an individual shard of a distributed memcached deployment.

The memory requirements of memcached are specified as a configration option before the memcached application is started. Knowing an upper bound on the amount of memory memcached can use allows memcached to claim the required memory and handle memory management itself rather than using *malloc, free or realloc. Slabs* are structured to be blocks of memory with 1MB allocated to them. Each slab belogns to a *slab group* which determines the size of each chunk inside the slab. By default, the minimum chunk size is 80 bytes with a hard maximum of 1MB. The growth factor between different slab groups is 1.25. Within each slab group, a Least Recently Used (LRU) eviction policy is employed effectively evicting entries least recently used within a similar memory requirement first.

Private networks are the intended target of memcached where applications designed to be publicly exposed access memcached on behalf of the requestor rather than exposing the cache directly. By default, memcached provides access to all entries of the cache for all clients but there is also an option to be used with a Simple Authentication and Security Layer (SASL) option.

Memcached is a multi-threaded application which introduces the requirement to lock resources during critical sections in order to prevent race conditions. The main reason for designing multi-threaded applications is improve performance. Parsing a request and understanding the nature of a request can be in parallel with data retrieval from memory while a response is being constructed, all in their own respective threads. However, in order to achieve the appearance of operation atomicity, a mutual exclusion lock is required. A request lifecycle is as follows [10]:

1. Requests are received by the Network Interface Controller (NIC) and queued
2. *Libevent* receives the request and delivers it to the memcached application
3. A worker thread receives a request, parses it and determines the command required
4. The *key* in the request is used to calculate a hash value to access the memory location in *O(1)*
5. Cache lock is acquired *(entering critical section)*
6. Command is processed and LRU policy is enforced
7. Cache lock is released *(leaving critical section)*

8. Response is constructed and transmitted

Given the outline above, we can see that steps 5. to 7. transform the parallel nature of processing a request into a serial process. Optimizations to the critical section have been well studied but it should be noted that memcahed suffers from overheads related to global lock acquizition and release.

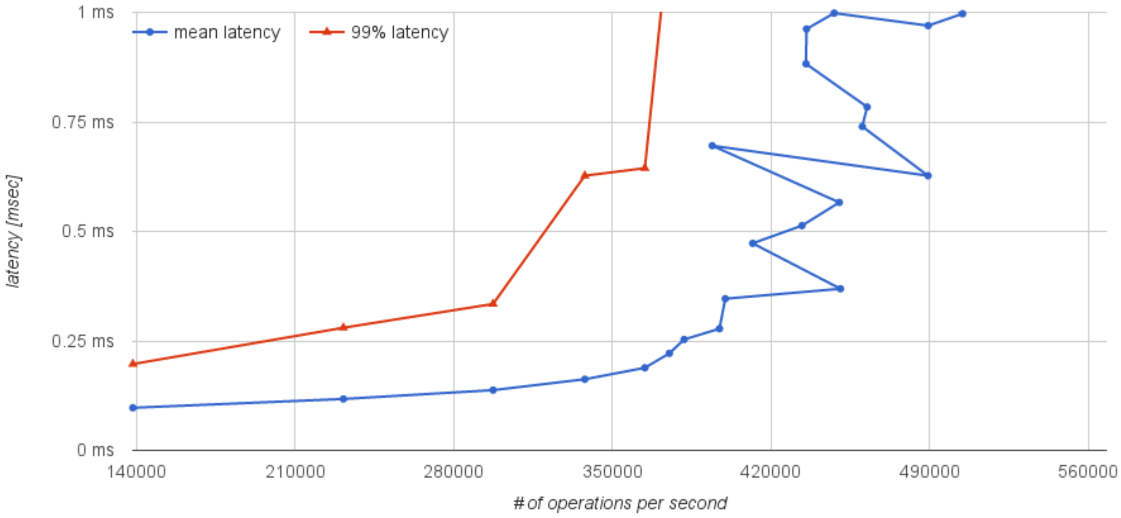
4.3 Configuration options

Memcached provides a convenient command line configration options to tweak the performance of memcached through various parameters, the most important ones are: * *-d* runs application in daemon mode * *-p* binds application to a port (18080 by default) * *-m* defines how much memory to allocate to memcached.

Given the host hardware has 8GB memory, 6GB will be allocated to memcached to leave some memory for the underlying operating system. Throughout this paper, mostly options outlined above will be utilized. Where applicable, further settings will be explained.

4.4 Throughput under QoS

Firstly, to establish a baseline it is essential to understand memcached behavior under high utilization. In order to establish this baseline, a default configuration of memcached will be used with a variable workload generated by the clients. Therefore, the memcached server is started with the following configuration `memcached -d -p 11120 -m 6144` setting the port and allocating 6GB of memory to memcached. Each memtier instance is configured with variable number of connections and treads such that the total number of connections (threads * number of connections per thread) is progressively increased. Memtier instances use the following configuration: `memtier -s nsl200 -p 11120 --test-time=60 -c <number of clients> -t <number of threads> -P memcache_binary --random-data --key-minimum=100 --key-maximum=10000`. The key size is capped between 100 and 10000 in order to simulate a realistic hit rate.



Throughput vs mean and 99th perecentile latency

From the figure above, we can see that both the mean latency and the 99th perecentile latency increases linearly until we reach a saturation point at which point each increase in throughput is met with a much larger increase in latency. Additionally, we can see that the highest throughput achieved with 99th percentile under 1ms is 375k operations per second. This corresponds to 84 simultaneous connections, or 12 connections per each client. This is similar to benchmarks used in the literature [11].

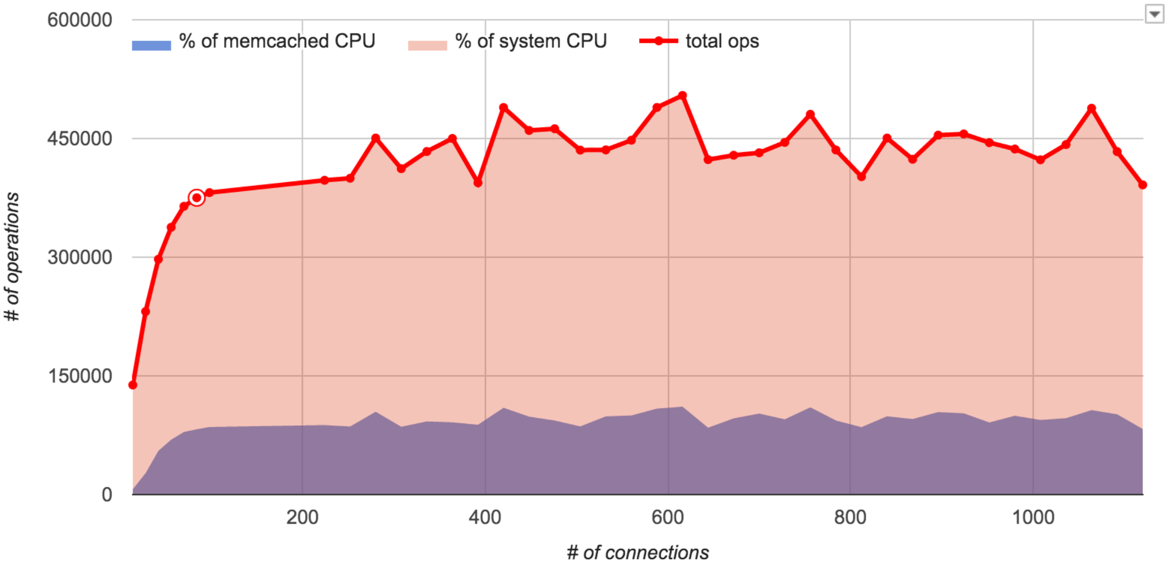


Figure 2: Memcached Default Configuration Baseline Connections vs Ops

In order to further understand the impact of an increase in the number of connections, consider the figure above comparing the number of connections with the number of operations executed. We can see that memcached scales well until we reach a saturation point at around 84 connections (highlighted). A further increase in the number of connections is met with a much lower increase in the total number of operations performed. The shaded segments under the curve represent the portion of CPU time spent processing memcached (blue) and in the system (red). Furthermore, we can see that when we reach the saturation point, memcached CPU usage remains consistent while all the remaining time is spent in the system. The system requires a large number of resources to process the incoming network requests and to process the outgoing requests from memcached. Finally, the diagram also demonstrates that memcached performance is tightly linked with the performance of the network stack and the underlying hardware responsible for handling incoming and outgoing communication. This is consistent with findings in other papers [12].

4.5 Memcached Thread Scalability

Memcached is designed to process requests in parallel and therefore a reasonable first step in scaling memcached is to provision more threads for the application. Considering that the benchmarking setup has a six-core processor, it is reasonable to expect the best performance when running memcached with six threads.

Utilizing findings from the previous section, configuration with 84 connections can be used to generate consistent load while the number of threads provisioned for memcached is increased. Therefore, each client is setup as follows: `memtier -s nsl200 -p 11120 --test-time=30 -c 6 -t 2 -P memcache_binary --random-data --key-minimum=100 --key-maximum=10000` and the server is configured with `memcached -d -p 11120 -m 6144 -t <threads>` where `<threads>` varies between 1 and 35.

The figure above shows mean and 99th percentile latency against the number of threads. The lowest mean latency occurs when running 6 threads of memcached. This corresponds to the expectation of best performance of using *n* threads with *n* CPU cores. Additionally, less than 6 threads exhibits higher latency than when using 6 cores. A constant load created against the server and the number of threads less than the number of CPUs creates a bottleneck where network requests targeted for a given core are attempted to be processed only by a given core to avoid an expensive data transfer and a context switch. Consequently, the queue of requests builds up and overall latency decreases. An increase in the number of threads allows for a higher throughput due to reduced bottleneck on request

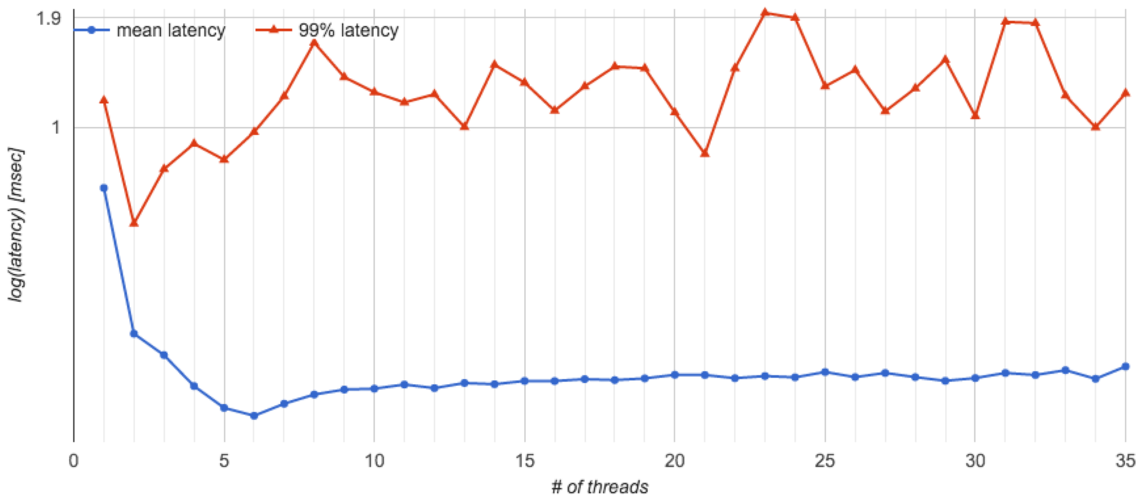


Figure 3: Memcached Thread Scaling

processing. Furthermore, latency increases with the number of threads as a context switch is required between contexts in each thread therefore putting additional strain on the operating system resources.

The 99th percentile lantecy behaves similarly to the mean latency. We can observe that 99th precentile latency drops below the defined quality of service when using between 2 and 6 threads. Beyond six threads, 99th percentile behavior fluctuates above the desired quality of service boundary.

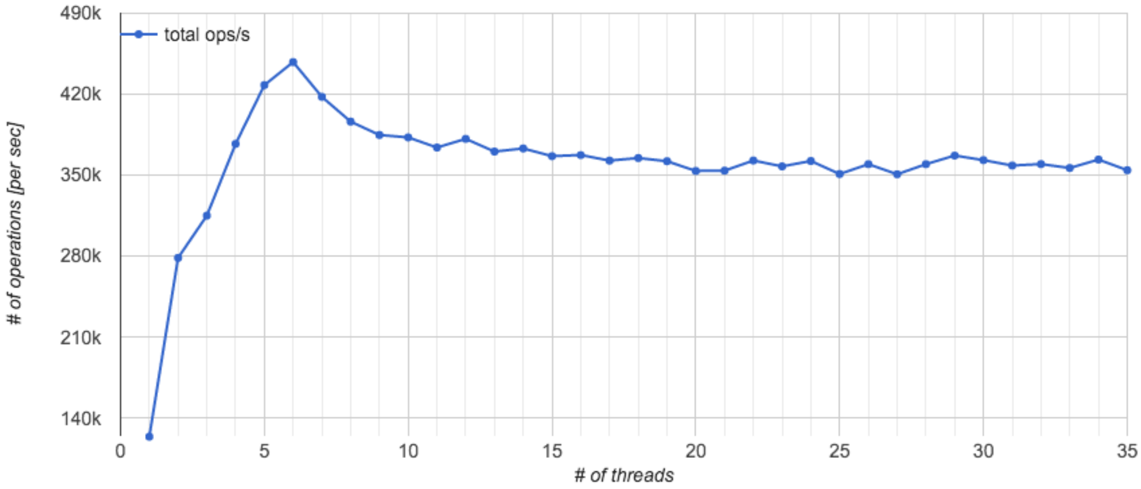


Figure 4: Memcached Thread Total Ops

Similarly to latency behavior, throughput is the highest when when running 6 threads - close to 450k operations per second. This is in accordance with our expectation as resources are being utilized fully and overhead from context switching is limited. Additionally, we can see that throughput incrases drastically between 1 and 6 threads, that is, from 120k to 450k. A further increase in the number of threads beyond 6 threads only results in a reduction in overall throughput caused by context switching overheads and operating system resource requirements.

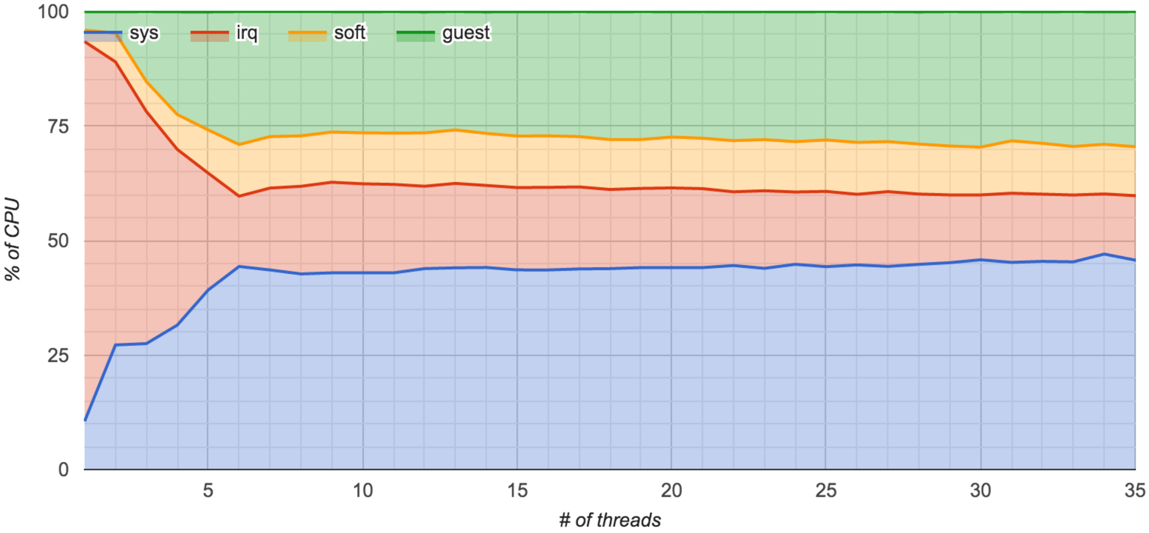


Figure 5: Memcached Thread CPU

Analysing the CPU usage as we increase the number of threads, we can observe that initially a large portion of the CPU time is spent servicing hardware interrupts (*irq*). Therefore, the OS is handling incoming traffic interrupts from the NIC. As the number of threads increases, an increasingly larger portion of CPU time is spent processing system calls and context switching (*sys*). This is reasonable as a larger number of threads will require context switching and concurrency management provided by the operating system. We can see that time spent processing hardware interrupts (*irq*) decreases which has the effect of increasing latency as packets remained queued up in the NIC for longer before the OS manages to schedule the interrupt to be serviced. Furthermore, we can observe that software iterrupts (*soft*) CPU time progressively increases until we reach 6 threads and remains stable as the number of threads grows further. The initial increase is reasonable as we are demanding more threads to processed simultanesly, past this point the percentage remains stable as we have reached a saturation point in terms of scalability and server performance. Finally, memcached (*guest*) follows a similar pattern as software interrupts. Usage increases until 6 threads are used and saturates further. This is further indicative of the inability to efficiently scale the number of threads past the point at which memcached uses the same number of threads as CPU cores.

4.6 Thread pinning

Thread pinning is the process of assigning a *set_irq_affinity* to each individual thread. As suggested by Leverich and Kozyrakis, “pinning memcached threads to distinct cores greatly improves load balance, consequently improving tail latency.” [13] and therefore the reasonable next step in optimizing memcached performance is to attempt thread pinning and analyse the results obtained.

By default, when a new process is started, its affinity is set to all available CPUs. We can discover a given process affinity by executing `taskset -p <pid>` where `pid` is the process identifier.

“A Memcache instance started with n threads will spawn n + 1 threads of which the first n are worker threads and the last is a maintenance thread used for hash table expansion under high load factor.” [14]. We can discover memcached threads used for request processing using `ps -p <memcache-process-id> -o tid= -L | sort -n | tail -n +2 | head -n -1` [14] and further set their processor affinity using `taskset -pc <cpu-id> <tid>` where is the thread id discovered previously [14].

Given the best performance under QoS constraints of 1ms found in the previous section is memcached with 6 threads, the following benchmark will be using this best configuration in order the analyze the impact of thread pinning.

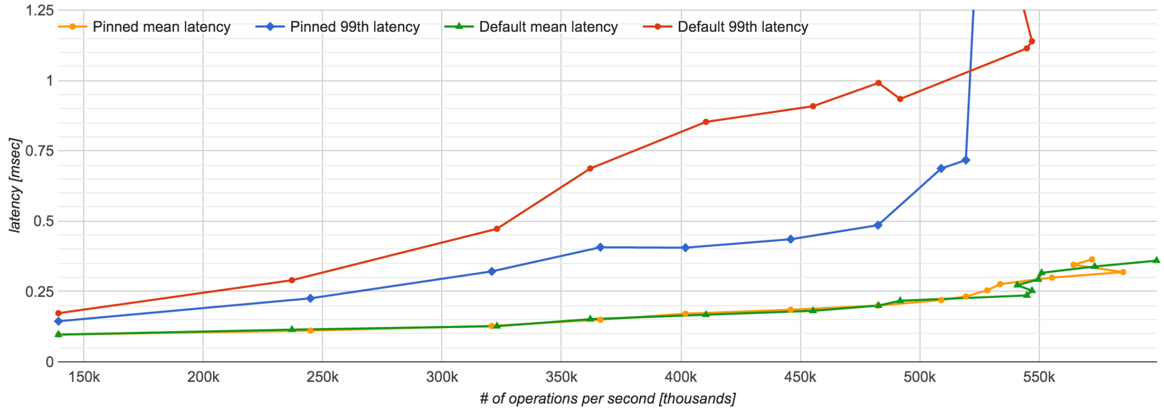


Figure 6: Memcached Pinned Threads vs Unpinned

- [1] memcached.org
- [2] An FPGA-based in-line accelerator for Memcached, Maysam Lavasani, Hari Angepat, and Derek Chiou

- [3] [New Commands, Memcached.org](https://code.google.com/p/memcached/wiki/NewCommands)
- [4] [Scaling memcached at Facebook](https://www.facebook.com/notes/facebook-engineering/scaling-memcached-at-facebook/39391378919/)
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- [7] Workload Analysis of a Large-Scale Key-Value Store, Berk Atikoglu, Yuehai Xu, Eitan Frachtenberg, Song Jiang, Mike Paleczny
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- [9] [Twemproxy](https://github.com/twitter/twemproxy)
- [10] [Enhancing the Scalability of Memcached](https://software.intel.com/sites/default/files/m/0/b/6/1/d/45675-memcached_05172012.pdf)
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- [12] MICA: A Holistic Approach to Fast In-Memory Key-Value Storage
- [13] Reconciling High Server Utilization and Sub-millisecond Quality-of-Service, Jacob Leverich Christos Kozyrakis
- [14] Filling The Pipe: A Guide To Optimising Memcache Performance On Solarflare Hardware