

**CRANFIELD UNIVERSITY**

Gabriel L. Muller

**HTML5 WebSocket protocol and  
its application to distributed  
computing**

**SCHOOL OF ENGINEERING**

Computational Software Techniques in Engineering

MSc

Academic Year: 2013 - 2014

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This thesis is submitted in partial fulfilment of the requirements for  
the degree of Master of Science

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# Declaration of Authorship

I, Gabriel L. Muller, declare that this thesis titled, HTML5 WebSocket protocol and its application to distributed computing and the work presented in it are my own. I confirm that:

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- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

# Abstract

HTML5 WebSocket protocol brings real time communication in web browsers to a new level. Daily, new products are designed to stay permanently connected to the web. WebSocket is the technology enabling this revolution. WebSockets are supported by all current browsers, but it is still a new technology in constant evolution.

WebSockets are slowly replacing older client-server communication technologies. As opposed to comet-like technologies WebSockets' remarkable performances is a result of the protocol's fully duplex nature and because it doesn't rely on HTTP communications.

The first part of this paper studies the WebSocket protocol and different WebSocket servers implementations. This first theoretic part focuses more deeply on heterogeneous implementations and OpenCL. The second part is a benchmark of a new promising library.

The real-time engine used for testing purposes is SocketCluster. SocketCluster provides a highly scalable WebSocket server that makes use of all available cpu cores on an instance. The scope of this work is reduced to vertical scaling of SocketCluster.

# Acknowledgements

I wish to thank my supervisor Mark Stillwell for accepting to work with me on this project. His positive suggestions and willingness to repeatedly meet and discuss the progress of this thesis have been invaluable.

Naturally, I am also grateful for the continuous support of my family and of my housemates. Always available and willing to provide either advises or distractions.

Lastly I would like to thank my colleague Léo Unbekannt. Not only did he help me in the very beginning when I was looking for a subject, but also later on through the whole thesis. More importantly our daily lunch conversations confirmed and raised my interest in computer science. Thanks Léo.

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# Abbreviations

<b>RFC</b>	Request For Comment
<b>HTTP</b>	HyperText Transfert Protocol
<b>HTML</b>	HyperText Markup Language
<b>TCP</b>	Transmission control protocol
<b>IP</b>	Internet Protocol
<b>UDP</b>	User Datagram Protocol
<b>OpenCL</b>	Open Computing Language
<b>OpenGL</b>	Open Graphic Library
<b>API</b>	Application Programming Interface
<b>GPU</b>	Graphic Processing Unit
<b>GPGPU</b>	General Purpose computation on GPU
<b>CPU</b>	Computing Processor Unit
<b>SIMD</b>	Single Instruction Multiple Data
<b>MIME</b>	Multi purpose Internet Mail Extension
<b>DSP</b>	Digital Signal Processing
<b>VCL</b>	Virtual open Computing Language
<b>TFLOPS</b>	Tera FLoating Operation Per Seconds

# Introduction

## **Problem statement**

WebSockets are implemented in a wide range of applications. As a result, a lot of different languages and specific libraries have been specifically developed for WebSockets.

The first part of this paper is an introduction to the WebSocket protocol and on the different implementation options when building a WebSocket cluster. In a second part, it focuses on the new real-time engine: SocketCluster and makes a benchmark of this library.

## **Thesis structure**

The first chapter is a literature review. The goal is to inform the reader about the WebSocket protocol and to go through the different WebSocket implementations. Therefore studying scalability and heterogeneous implementations.

The third chapter is an introduction to the experiments. It is dedicated to the design and the implementation of the infrastructure used later on. It mostly introduces the benchmark library used.

The experiment chapter is a comprehensive benchmark of SocketCluster. It compares the performances to a classic engine.io implementation and also studies the limitations of the library.

To finish the last part concludes this thesis and suggest future work on SocketCluster.

# Chapter 1

## Literature review

This chapter is an introduction to the WebSocket protocol. It begins with a section which sums up client-server communication techniques. The second section is an in depth study of WebSockets.

This chapter present past and current research on WebSockets. The first section is about the implementation of WebSockets server, the second is about scalability.

### 1.1 Client-server communications

This section studies the evolution of client-server communication, beginning with the page by page model until current technologies. However as an introduction, the first part is about HTTP which is the foundation of client-server communication.

#### 1.1.1 HTTP protocol

The HTTP protocol is a request/response protocol defined in the request for comment (RFC) [1] as follows:

A client sends a request to the server in the form of a request method, URI, and protocol version, followed by a MIME-like message containing request modifiers, client information, and possible body content over a connection with a server. The

server responds with a status line, including the message's protocol version and a success or error code, followed by a MIME-like message containing server information, entity meta information, and possible entity-body content.

Because HTTP was not designed for real time communication several workarounds have been developed over the years to overcome the so called page by page model. These techniques are Explained in details in Eliot Step master thesis [2].

### 1.1.2 Page by page model

Since HTTP's release in 1991, client-server communication have undergone continuous upgrades. In the early nineties, most web pages were static. As a consequence, the communication between client and server were rather limited. Typically, the client would send occasional request to the server. The server would then answer, but all communication would stop there until a new event was triggered by the user.

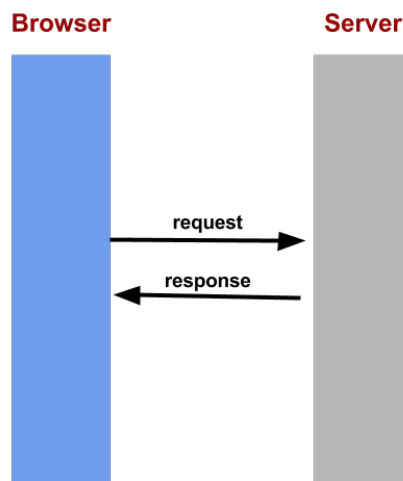


FIGURE 1.1: Client-server communication

The notion of dynamic web appeared in 2005 with the introduction of technologies like Comet. Peter Lubbers describes it as the Headache 2.0 in his article "A quantum leap in scalability for the web" [3].

### 1.1.3 Polling

Polling was the first attempt toward real-time communication. Instead of waiting for the client to manually ask for a page update, the browser would send regular HTTP GET requests to the server. This technique could be efficient if the exact interval of update on the server side was known.

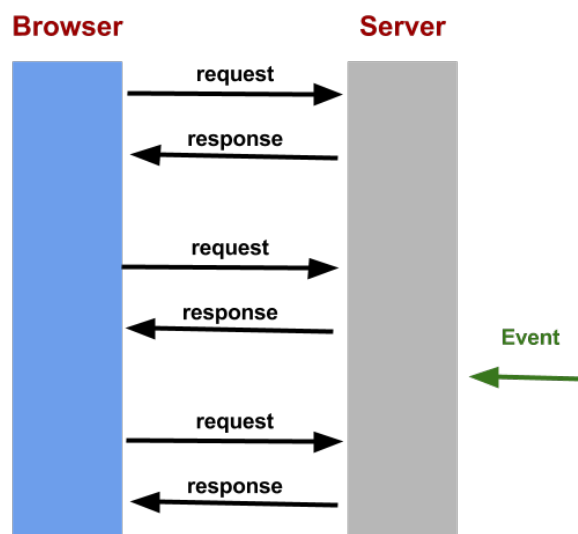


FIGURE 1.2: polling

However real time information is unpredictable and in high updates rate situation like stock prices, news reports or tickets sales the response could be stale by the time the browser renders the page [3].

Also in low updates rate situation even if no data is available, the server will send an empty response. This would result in a large amount of unnecessary

connections being established, which over time and with the clients increase would lead to decreased overall network throughput [2].

### 1.1.4 Long polling

Long polling is based on Comet technologies and is a slight step further toward server sent events and real time communication. Comet began to be popular in web browser around 2007, it is a family of web techniques that allows the server to hold an HTTP request open for prolonged periods of time.

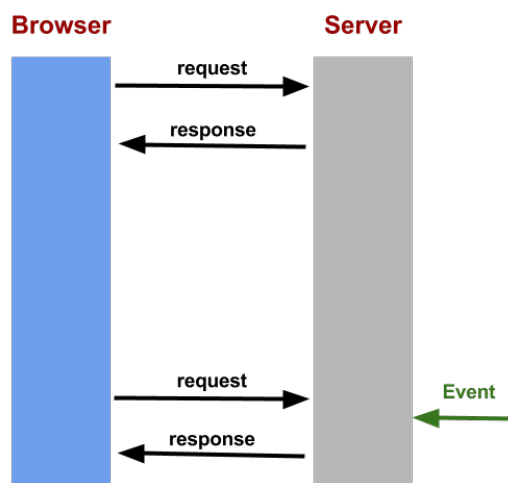


FIGURE 1.3: Long polling

Long-polling is similar to polling, except that the server keeps the HTTP request open if data is not immediately available. The server determines how long to keep the request open, request also known as a **hanging GET**. If new data is received within the time interval, a response containing the data is sent to the client and the connection is closed. If new data is not received within the time period, the server will respond with a notification to terminate the open request and close the connection. After the client browser receives the response, it will create another request to handle the next event, therefore always keeping a new long-polling

request open for new events. This results in the server constantly responding with new data as soon as it is made available [2].

However, in situations with high-message volume, long- polling does not provide increased performance benefits over regular polling. Performance could actually be decreased if long-polling requests turn into continuous, unthrottled loops of regular polling requests.

### 1.1.5 Streaming

Streaming is based on a persistent HTTP connection. The communication still begins with a request from the browser, the difference is in the response. The server never signals the browser its message is finished. This way the connection is kept open and ready to deliver further data [2].

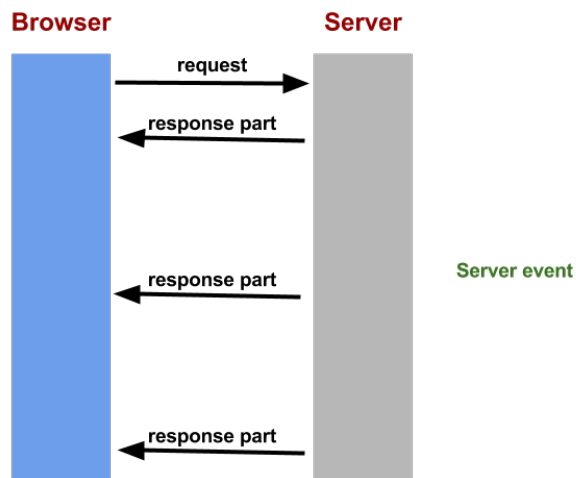


FIGURE 1.4: Streaming

If it wasn't for proxies, streaming would be perfectly adapted for real time communication. Because streaming is done over HTTP, proxy server may choose to



buffer server responses and thus increasing greatly the latency of the message delivery. Therefore in case a proxy is detected most Comet-like solution fall back to long polling [2].

### 1.1.6 Current technologies in browsers

At the moment, comet technologies are still the most popular way of communication between browsers and servers. Techniques has been improved to the point where it perfectly fakes server sent event. Comet technologies can be seen as a wonderful hack to reach real time communication. However little can be done to improve the latency. Comet technologies revolve around HTTP and carry its overhead.

The total overhead from the HTTP request and response header is at least 871 bytes without containing any data. In comparison, a small payload is 20 bytes. Contemporary application like on-line games can not be built on a technology wasting resources equivalent to 40 messages every time information is exchanged [2]. Therefore a brand new protocol has been developed: WebSocket.

## 1.2 WebSocket protocol

The creation of the WebSocket protocol marks the beginning of the Living web. It is often referred to as the first major upgrade in the history of web communications. As the Web itself originally did, WebSocket enables entirely new kinds of applications. Daily, new products are designed to stay permanently connected to the web. Websocket is the language enabling this revolution.

This section is a study of the WebSocket protocol. Firstly it defines the protocol. Secondly it studies how to establish a WebSocket connection. Afterwards it goes on with an in depth study of WebSockets' transport layer and frame anatomies. Lastly it provides a brief discussion of WebSockets' interaction with proxies.

### 1.2.1 Definition

The official Request For Comments [4] (RFC) describes the WebSocket protocol as follows:

The WebSocket Protocol enables two-way communication between a client running untrusted code in a controlled environment to a remote host that has opted-in to communications from that code. The security model used for this is the origin-based security model commonly used by web browsers. The protocol consists of an opening handshake followed by basic message framing, layered over TCP. The goal of this technology is to provide a mechanism for browser-based applications that need two-way communication with servers that does not rely on opening multiple HTTP connections.

To Initiate a WebSocket communication, first a HTTP handshake needs to be done.

### 1.2.2 The WebSocket handshake

The Websocket protocol was to be released in an already existing web infrastructure. Therefore it has been designed to be backward-compatible. Before a Websocket communication can start, a HTTP connection must be initiated. The browser sends an Upgrade header to the server to inform him he wants to start a WebSocket connection. Switching from the HTTP protocol to the WebSocket protocol is referred to as a handshake [4].

```
GET ws://websocket.example.com/ HTTP/1.1
Origin: http://example.com
Connection: Upgrade
Host: websocket.example.com
Upgrade: websocket
```

If the server supports the WebSocket protocol, it sends the following header in response.

HTTP/1.1 101 WebSocket Protocol Handshake

Date: Wed, 5 May 2014 04:04:22 GMT

Connection: Upgrade

Upgrade: WebSocket

After the completion of the handshake the WebSocket connection is active and either the client or the server can send data. The data is contained in frames, each frame is pre-fixed with a 4-12 bytes to ensure the message can be reconstructed.

Once the server and the browser have agreed on beginning a WebSocket communication. A first request is made to begin an ethernet communication followed by a request to make an TCP / IP communication.

### 1.2.3 Transport layer protocol

The internet is based on two transport layer protocols, the User Datagram Protocol (UDP) and the Transmission Control Protocol (TCP). Both use the network layer service provided by the internet protocol (IP).

#### TCP

TCP is a reliable transmission protocol. The data is buffered byte by byte in segments and transmitted according to specific timers. This flow control ensure the consistency of the data. TCP is said to be a stream oriented because the data is sent in independent segments.

#### UDP

UDP is unreliable but fast. The protocol offers no guaranty the data will be delivered in its integrity nor duplicated. It works on a best effort strategy with no flow control. Each segments are received independently, it is a message oriented protocol.

Websocket is build over TCP because of its reliability. Browser enabled games are the perfect example of WebSockets' use cases. They require low latency and have a high rate of update. To achieve low latency, the communication protocol must make sure not to drop any packets. Otherwise, the exchange takes two times longer.

As can be inferred from the 2 previous subsections, the websockets protocol relies on a few other protocols. Namely HTTP to initialize the communication, ethernet, TCP/IP and finally TLS in case a secure connections is required. The next subsections studies the influence this protocols have in the anatomy of WebSockets frame.

### 1.2.4 The WebSocket frame anatomy

The study conducted by Tobias Oberstein [5] looks into the overheads of websockets. As a matter of fact the overhead induced purely by WebSockets is extremely low. As can be seen in the figure 1.5, depending on the size of the payload the overhead varies between 8 and 20 bytes.

Payload	Client-to-server	Server-to-client
<126	6	2
<64k	8	4
<2**63	12	8

FIGURE 1.5: Frame overhead [5]

However, as pointed out in the article efficiency is lost on protocols of other layers required for WebSocket's functionment. Figure 1.6 and 1.7 respectively show the overhead induced by pure TCP/IP and TLS protocols.

TLS		bytes on wire	ether frames	TCP segments	TLS records	app payload
Chrome 34	TLS 1.2	816	8	8	8	104
Autobahn (response)	TLS 1.2	406	1	1	8	104

FIGURE 1.6: TLS overhead [5]

plain TCP		bytes on wire	ether frames	TCP segments	app payload
Chrome 34		584	8	8	104
Autobahn (response)		174	1	1	104

FIGURE 1.7: TCP overhead [5]

In this example, the payloads `Hello world` is only thirteen bytes. In comparison ethernet, TCP/IP and TLS protocols each use height bytes. The conclusion of

this article is to warn programmers about the size of the payloads so that all the protocols revolving around WebSockets don't dwarf the overhead of the WebSocket protocol itself. In case small payloads can not be avoided a possible solution is to serialize the messages in order to batch them in one single WebSocket message.

So instead of sending the each messages using the WebSocket protocol like shown in figure 1.8. The individual messages are put in a queue and batched in a single Websocket message like in figure 1.9.

```
TCP/IP segment | TLS header | WebSocket header | WebSocket message_1 payload
TCP/IP segment | TLS header | WebSocket header | WebSocket message_2 payload
TCP/IP segment | TLS header | WebSocket header | WebSocket message_3 payload
```

FIGURE 1.8: WebSocket messages sent individually [5]

```
TCP/IP segment |
  TLS header |
    WebSocket header |
      WebSocket message_1 payload
      WebSocket message_2 payload
      WebSocket message_3 payload
```

FIGURE 1.9: Batched WebSocket messages [5]

Nevertheless, WebSockets carry way less overhead then comet technologies do. Another advantage of WebSocket its interaction with proxies.

### 1.2.5 Proxies

Proxy servers are set up between a private network and the Internet. They act like an intermediary providing content caching, security and content filtering.

When a Websocket server detects the presence of a proxy server, it automatically sets up a tunnel to pass through the proxy. The tunnel is established by issuing an HTTP CONNECT statement to the proxy server, which requests for the proxy server to open a TCP/IP connection to a specific host and port. Once the tunnel is set up, communication can flow unimpeded through the proxy.

To sum up compared to comet technologies, WebSockets are:

- As reliable, because they are also built over TCP
- Way faster, because they don't carry the overhead of HTTP
- Behaving better in presence of proxies
- Fully bidirectional

The nexts sections of this chapter are dedicated to the implementation of WebSockets servers.

## 1.3 Implementation

As in any project, in order to avoid future technical problems, it is better to first study similar projects. The goal of this implementation study is to find a suitable language and possibly a good library to run the experiment.

### 1.3.1 WebSocket server implementation

In order to narrow the library study, first a language needs to be selected.

#### Language Selection

Choosing a language for a project is often a compromise between the programmers development background and the necessity of the application. Furthermore, WebSocket servers can be developed in almost any languages.

This subsection does not aim at giving a comprehensive comparison of all existing WebSocket friendly languages. Node.js seems to be the perfect environment for this study, therefore other languages will deliberately be left out and the focus will be on explaining why Node.js is appropriate.

Node.js was specially invented to create real-time websites with push capabilities [6]. Most languages run parallel tasks by using threads but threads are memory expensive. Node.js is fundamentally different, it runs as a single non-blocking

and event-driven loop by using asynchronous call back loops [7]. For this reasons, compared to other languages, Node.js performs significantly better in highly concurrent environment.

Node.js has many real-time engines. The next step is to carefully make a choice between ws, Socket.io and Engine.io.

### **WebSocket implementation selection**

Deniz Ozger article's for medium.com [8] is a comprehensive study of node.js real-time engines.

Ws is a pure WebSocket implementation, therefore it is appropriate for testing purposes but seldom used in real life projects. The main drawback is the communication may not work in case the browser does not support WebSockets.

Socket.io has some appreciable features namely its connection procedure. First it tries to connect to a server via WebSocket, in case it fails it downgrades until it finds a suitable protocol. Moreover it tries to reconnect sockets when connections fail.

Engine.io is a lower library of Socket.io. The connection procedure is the opposite to Socket.io though. It first establishes a long polling connection and only later tries to upgrade it to a better transport protocol. Therefore it is more reliable because it establishes less connection.

In conclusion, Node.js and its real-time library engine.io seems to best choice for our study. However better performance could be reached using an heterogeneous implementation.

### **1.3.2 Heterogeneous implementation with OpenCL**

As suggest John Stone paper's title "OpenCL: A parallel programming standard for heterogeneous computing systems" [9] OpenCL is unanimously considered as the reference for heterogenous computing.

Historically, the first technology to take advantage of the massive parallel nature of GPUs was Open Graphic Library (OpenGL). OpenGL is an application programming interface (API) for rendering 2D and 3D vector graphics. Through the

insertion of little pieces of C-like codes in shader, developers soon realized graphic processing units (GPUs) could also be used for general programming. This became known as General Purpose computation on GPUs (GPGPU) [9].

However, shaders can only be modified so much. As the need for more complex applications arose, Apple proposed the Khronos Group to develop a more general framework: OpenCL. OpenCL is a low-level API accelerating applications with task-parallel or data-parallel computations in a heterogeneous computing environment. Indeed OpenCL not only allows the usage of CPUs but also any processing devices like GPUs, DSPs, accelerators and so on [9]. If generally, on desktops the diversity of processing devices is quite low, as opposed to mobile devices. Embedded systems for real-time multimedia journal published a paper [10] highlighting the advantages of using OpenCL in mobile browser.

OpenCL doesn't guarantee a particular kernel will achieve peak performance on different architectures. The nature of the underlying hardware may induce different programming strategies. Multi-core CPU architecture is definitely the more popular. But the recent specification published by Khronos to take GPU computing to the web is bound to raise programmers interest toward GPUs architecture [5].

### **CPUs architecture**

Modern CPUs are typically composed of a few high-frequency processor cores. CPUs perform well for a wide variety of applications, but they are optimal for latency sensitive workloads with minimal parallelism. However, to increase performance during arithmetic and multimedia workloads, many CPUs also incorporate small scale use of single instruction multiple data (SIMD).

### **GPUs architecture**

Contemporary GPUs are composed of hundreds of processing units running at low frequency.

As a result GPUs are able to execute tens of thousands of threads. It is this ability which makes them so much more effective than CPUs in a highly parallel environment. Some research even claim a speedup in the order of 200x over JavaScript. [10]



The GPU processing units are typically organized in SIMD clusters controlled by single instruction decoders, with shared access to fast on-chip caches and shared memories. Massively parallel arithmetic-heavy hardware design enables GPUs to achieve single-precision floating point arithmetic rates approaching 2 trillions of instructions per second (TFLOPS). [9]

Although GPUs are powerful computing devices, currently they still often require to be management by a host CPU. Fortunately OpenCL is designed to be used in heterogeneous environment. It abstracts CPUs and GPUs as compute devices. This way, applications can query device attributes to determine the properties of the available compute units and memory systems. [9]

All the same, even if OpenCL's API hides the hardest part of parallel programming a good understanding of the underlying memory model leads to more efficient coding. Along with general advises on how to build an OpenCL cluster, details about the memory model are given in the following paper: [11].

### Platform model

CPU and GPU are called compute devices. A single host regroups one or more compute devices and has its own memory. Each compute device is composed of one or more cores also called compute units. Each compute unit has its own memory and is divided into one or more SIMD threads or processing elements with its own memory. [11]

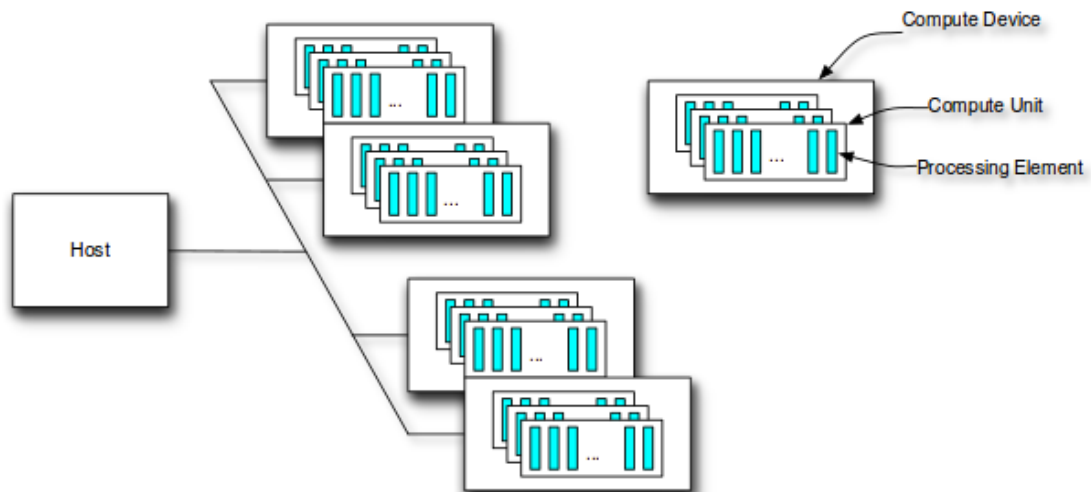


FIGURE 1.10: Platform model [11]

### Memory model

OpenCL defines 4 types of memory spaces within a compute device. A large high-latency global memory corresponding to the device RAM. This is a none cached memory where the data is stored and is available to all items. A small low-latency read-only constant memory which is cached. A shared local memory accessible from multiple processing elements within the same compute unit and a private memory accessible within each processing element. This last type of memory is very fast and is the register of the items [11].

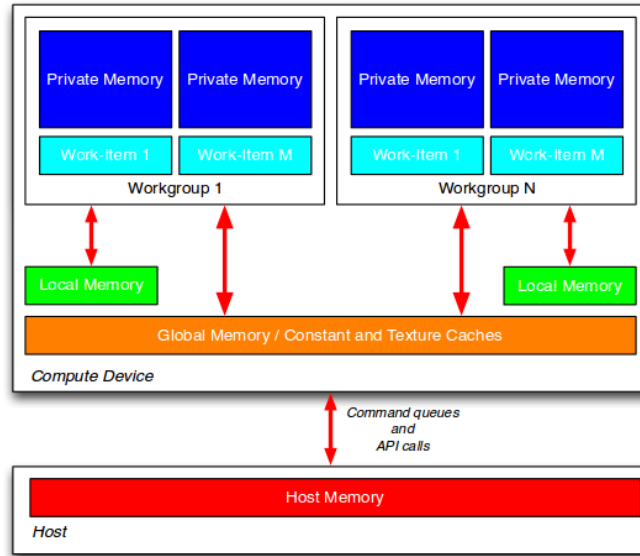


FIGURE 1.11: Memory model [11]

In conclusion, OpenCL provides a fairly easy way to write parallel code but to reach an optimal performance / memory access trade off programmers must choose carefully in where to save their variables in memory space.

### Global and local IDs

Finally, at an even lower level, work-items are scheduled in workgroups. This is the smallest unit of parallelism on a device. Individual work-items in a workgroup start together at the same program address, but they have their own address counter and register state and are therefore free to branch and execute independently [11].

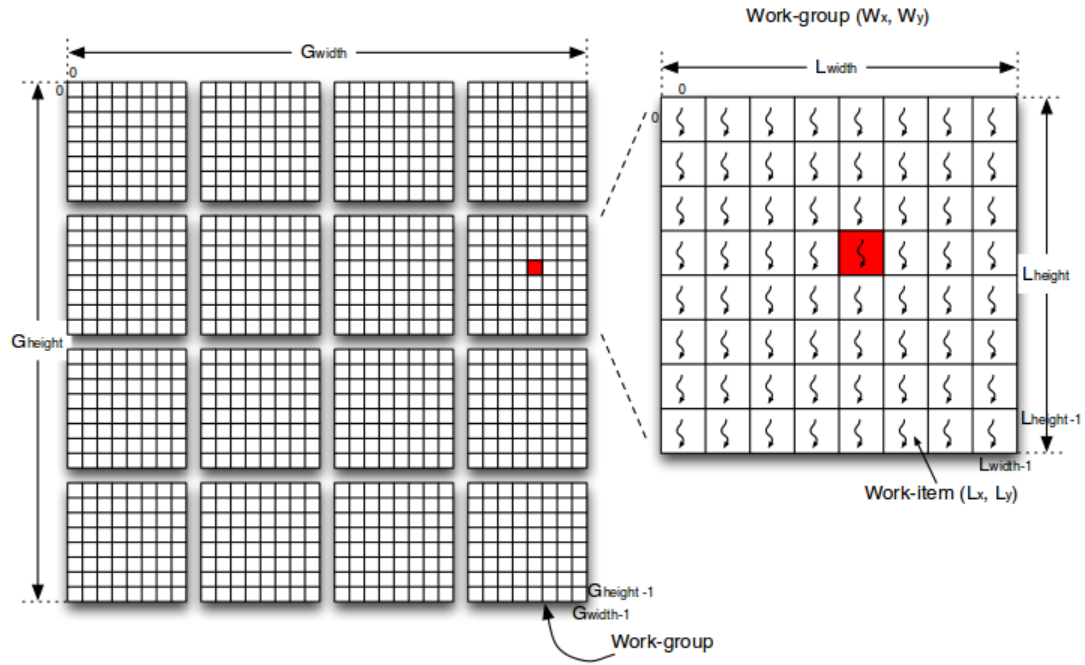


FIGURE 1.12: Work Group [11]

On a CPU, operating systems often swap two threads on and off execution channels. Threads (cores) are generally heavyweight entities and those context switches are therefore expensive. By comparison, threads on a GPU (work-items) are extremely lightweight entities. Furthermore in GPUs, registers are allocated to active threads only. Once threads are complete, its resources are de-allocated. Thus no swapping of registers or state occurs between GPU threads. [11]

It can be deduced from this section that the underlying memory model, OpenCL is a fairly low-level API. In fact, the programming language used is a derivative of the C language based on C99. A language web developers will most likely be unfamiliar with. Khronos anticipated this and developed the web computing language (WebCL).

### 1.3.3 WebCL

WebGL and WebCL are JavaScript APIs over OpenGL and OpenCL's API. This allows web developers to create application in an environment they are used to.

In the first place, OpenCL was developed because of web browsers' increasing need for more computational power. A necessity which arose from heavy 3D graphics applications such as on-line games and augmented reality. However, OpenCL doesn't

provide any rendering capability, it only processes huge amounts of data. That is why OpenCL was designed for inter-operation with OpenGL. WebCL/WebGL interoperability builds on that available for OpenCL/OpenGL. WebCL provides an API for safely sharing buffers with OpenCL. This buffer is inside the GPU which avoids the back and forth copy of data when switching between OpenGL and OpenCL processes. Further precision about the interoperability are discussed in this paper: [12].

GPU computing is quite a new notion. But it is a fast evolving field of research. Single GPUs are not enough anymore, the trend is moving towards GPU clusters.

### 1.3.4 GPU clusters

Most OpenCL applications can utilize only devices of the hosting computer. In order to run an application on a cluster, the program needs to be split to take advantage of all devices. Virtual OpenCL (VirtualCL) is a wrapper for OpenCL. It provides a platform where all the cluster devices are seen as if located on the same hosting node. Basically, the user starts the application on the master node then VirtualCL transparently runs the kernels of the application on the worker nodes. Applications written with VirtualCL don't only benefit from the reduced programming complexity of a single computer, but also from the availability of shared memory and lower granularity parallelism. Mosix white paper [13] explains more in depth the VCL's functionment.

OpenCL and VirtualCL are powerful tool to create highly parallel clusters. But current implementation with CPUs only already reach a million concurrent connections [14]. So far there is simply no need for more powerful clusters.

However, all company don't have access to dual Quad-core Xeon CPUs used in Kaazing cluster to reach a million concurrent connections. Usual practice is to build a scalable cluster, to adjust computing power in function of the needs.

## 1.4 Scalability

The growth of distributed computing has changed the way web application are designed and implemented. If compared with today standards, applications used

to be deployed so as to say at prototype stage. That is, they were designed to work on a fixed number of servers and not able to adjust as the user base grows. As the number of connections increase, the load on the servers rises and thus the latency grows. Ideally, an application should aim at a stable latency, otherwise the application can miss behave.

On the server side, the nodes will begin to be overloaded and struggle to service the client with reasonable response time.

Also, if the servers are overwhelmed they buffer the responses to the clients and then catch up later on . As a result, the clients can be flooded when the load goes down. The sudden rush of message can provoke an unexpected behavior from the servers and can even lead to disconnections.

Nowadays, designing an application without scalability and load balancing in mind is unimaginable. Historically, the reaction to an overloaded server has always been to scale up.

### **1.4.1 Scaling up**

Scaling up or vertically basically means upgrading the infrastructure. Depending on the needs of the application, the processor, the memory, the storage or the network connectivity can be improved.

Further performance can be gained by dividing tasks. It only requires identification of the services running independently or the using message based communication. Those could then be relocated on different nodes.

The main advantage of scaling vertically is that it does not involve any software changes and little infrastructure changes. Therefore it is an easy way to increase performances. However for large applications, scaling up might prove impossible or at least not economically profitable. In case the infrastructure is already equipped with the latest hardware generation, the tiniest increase in performance will impact greatly the price. For example, a high range processor offering ten percent more computation power is going to be many times more expensive. Similarly, a memory upgrade could require replacing all current modules for higher density ones.

Moreover, scaling up neither answers availability nor uptime concerns. The system is monolithic and has a single point of failure. Therefore contemporary project usually scale out and use parallel computing.

### 1.4.2 Scaling out

Scaling out or horizontally, answers most of the problems unsolved by scaling vertically. In a first approach lets ignore the software complexity. Scaling out offers almost unlimited performance increase and at low cost. If the application is designed to be spread out on multiple nodes, the performance of an infrastructure can be doubled by simply using twice as many servers. Also it is fairly easy to add some redundant server to insure uptime. Plus, compared to scaling up, once the software is developed the costs are linear.

When scaling out, the infrastructure implementation is not as much of a problem as the code implementation. The expenses are shifted from hardware to development costs.

#### Code implementation

Developing a parallel code is quite complicated and all applications can not be paralyzed. In 1967 Gene M. Amdahl defined the so called Amdahl's law which is still used today to define the maximum to expect when parallelizing a code [15].

Each software can be divided in two separate parts, the parallel part and the sequential part. Parallel computing does not improve the sequential part. If a the code is mainly sequential, then increasing the number of processors will only cause the parallel part to finish first and stay idle waiting for the sequential part to finish.

Assuming  $P$  is the portion of a program that can be parallelized and  $1 - P$  is the portion that remains serial, then the maximum speedup that can be achieved using  $N$  processors is:

$$speedup(N) = \frac{1}{(1 - P) + \frac{P}{N}}$$

If 70% of the program can be run in parallel ( $P = 0.7$ ) the maximum expected speedup with 4 processors would be:

$$speedup(N) = \frac{1}{(1 - 0.7) + \frac{0.7}{N}}$$

$$speedup(4) = 2.1$$

When the number of processors reaches a certain point, the speed up will be:

$$\lim_{N \rightarrow \infty} speedup(N) = \frac{1}{1 - P} = 3.3$$

Nathan T. Hayes's paper for Sunfish Studio [16] studies how parallel computing can profit the motion picture Industry. The following chart present the maximum speedup which can be expected from an application in function of the percentage of parallel code in the programme.

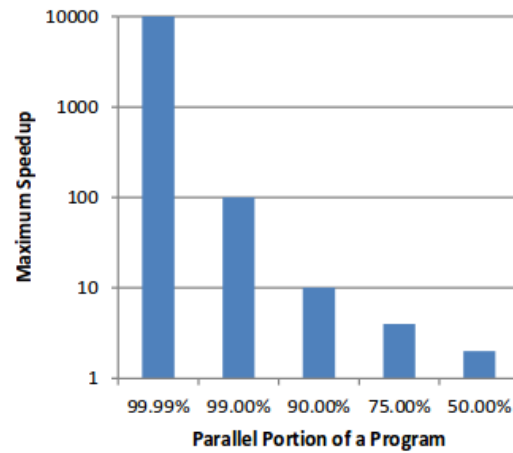


FIGURE 1.13: Amdahl law [16]

The figure speaks for itself, to envisage parallel computing, the portion of parallel code must be very high.

However, Amdahl's law is based on assumption which are hardly verified in practice. Following are summed up reasons not to give too much importance to Amdahl's law [17]:

- The number of threads is not always equivalent to the number of processors.

- The parallel portion does not have a perfect speedup. Computation power is used for communication between processes. Also some resources like caches and bandwidth have to be shared across all the processors.
- Allocating, deallocating and switching threads introduces overhead, overhead grows linearly with the number of thread.
- Even an optimized code will not have perfectly synchronised threads, at some point some processes will have to wait for others to finish.

Amdahl's law has long been used as an argument against massively parallel processing. In 1988 Gustafson law came as an alternative to Amdahl's law to estimate the speedup. In both law, the sequential portion of the problem is supposed to stay constant. But in Gustafson's law the overall problem size grows proportionally to the number of cores. As a result, Gustafson's gives slightly different results to Amdahl's and encourage the use of parallel computing.

However later studies tends to contest the legitimacy of both laws. Yuan Shi's paper [18] even proves both theories are but two different interpretations of the same law. He concludes his study by saying these laws are too minimalist and what computer scientist really need is a practical engineering tool that can help the community to identify performance critical factors.

### **Infrastructure implementation**

Beside coding complication, scaling out also brings infrastructure changes. A third party must be in command of all servers. This master server is also called load balancer. Its role is to distribute the work evenly between the workers and thus completely hides the complexity to the user.



# Chapter 2

## Design and Implementation

Current research around WebSocket is centered around distributed computing. Either on CPUs architecture, GPUs architecture or heterogeneous architecture. For the time being, clustering WebSocket servers is rather difficult and reserved to researcher or specialized companies. Actually in Node.js, there is hardly any library to simply and efficiently implement a multi-core server. Node.js single thread nature is a double edge sword. On one side it allows more concurrent connections to be established but it also means special attention needs to be given to run the code on all the servers cores. SocketCluster is a brand new real-time engine aiming exactly at that. At this point of my thesis I had to make a choice between either the theoretical study of WebSocket clusters or the benchmarking of SocketCluster. After contacting Jonathan Gros-Dubois, the creator of SocketCluster, I made up my mind for the latter. Indeed, SocketCluster being under development the tests carried out so far are rather sparse.

### 2.1 SocketCluster library

As described on the github project [19], SocketCluster is a fast, highly scalable HTTP and WebSocket server. It facilitates the creation of multi-process real-time application that make use of all CPU cores on a machine/instance. Therefore removing the limitations of having to run a Node.js server as a single thread. SocketCluster's focus is on vertical scaling. If  $N$  is the number of cores available on the server, then SocketCluster is  $N$  time faster than any comparable single-threaded WebSocket server. Under the hood, the application deploys itself on all available

cores as a cluster of process. The process can be grouped in three categories: stores, workers and load balancers.

## 2.2 Challenges encountered using SocketCluster

At first my study of SocketCluster was far from satisfactory. Past a total of 512 communications channel, new sockets were inexplicably crashing.

### U-limit

This comes from a system limit set up on linux operating systems. By default the maximum number of file that can be sent over tcp is 1024.

Fortunately, this limit can be increased by appending this line: `ubuntu soft nofile "number of file"` in `/etc/security/limits.conf`

Once this problem was fixed I looked into a benchmark to carry out, Jonathan Gros-Dubois advised me to focus on concurrent connections tests.

### C 10K Problem

The C 10K is an historic challenge issued in 1999 by Dan Kegel. It consist of reaching 10 000 concurrent client connections. Engineers solved this problem by fixing operating systems kernel and creating new single threaded programming languages like Node.js.

Therefore one of my objectives while testing SocketCluster was to see how many concurrent connections it can handle.

However this should not be a problem for this library, contemporary objective is rather to achieve 10 000 000 concurrent connections like mentioned in the excellent article in [highscalability.com](http://highscalability.com) [20]. Such amount of connections is beyond the scope of this thesis, but apparently the solution to improve the number of connections is to move heavy lifting from the kernel to the application itself.

Another topic to consider before begin testing was how to monitor the application.

## 2.3 Monitoring tool

Monitoring tools can be divided in two categories. Basic Real time monitoring and more convenient tool saving statics in spreadsheets and eventually even directly plotting graphs. Most of them can be configured to record processor load on each cores. But ideally SocketCluster tests would require to record each threads load's. This way, if run less process than available cores are being run the exact usage of each thread can still be found.

For this reason and also to have more freedom on how data is being processed, out of the box tool have been cast aside for more basic tools like top and htop. htop has been used to visualize data in real time and check if the test was running flawlessly. top has been used in batched mode to output the data in files.

In a latter phase, bash operation is used to format the raw data extracted from top's file. And finally, graphs are plotted with gnuplot.

# Chapter 3

## Experiment

This chapter is a comprehensive benchmark of SocketCluster. to begin with, the scalability of the client code will be checked with a client throughout test. Then once the the client has been proof checked, the first experiment will compare SocketCluster and engine.io.

Then the experiment will purely focus on SocketCluster. The first one will evaluate the influence of adding more cores on the performances. The second one will study the influence of external parameters like the period of pings, the size of the messages and the number of communications. And to finish a concurrent experiment will be carried out in order to have an idea of SocketCluster's behavior in highly parallel environment.

### 3.1 Client throughout

This first section is composed of two experiment to check the client code is behaving like expected.

#### 3.1.1 Client scalability

SocketCluster-client makes the instantiation of a WebSocket clients on one core quite straightforward. To deploy it on all available nodes, node.js `fork()` function is used. A client code example is given in appendix A.1.

The first experiment is a safety test. It checks if `fork()` distributes evenly the work among the cores.

Parameters	
Instance type	amazon s3 m3.2xlarge
Experiment time	120 s
Number of new communication created at each iteration	15
Client creation period	1 s
Type of ping	random number
Ping period	2.5 s

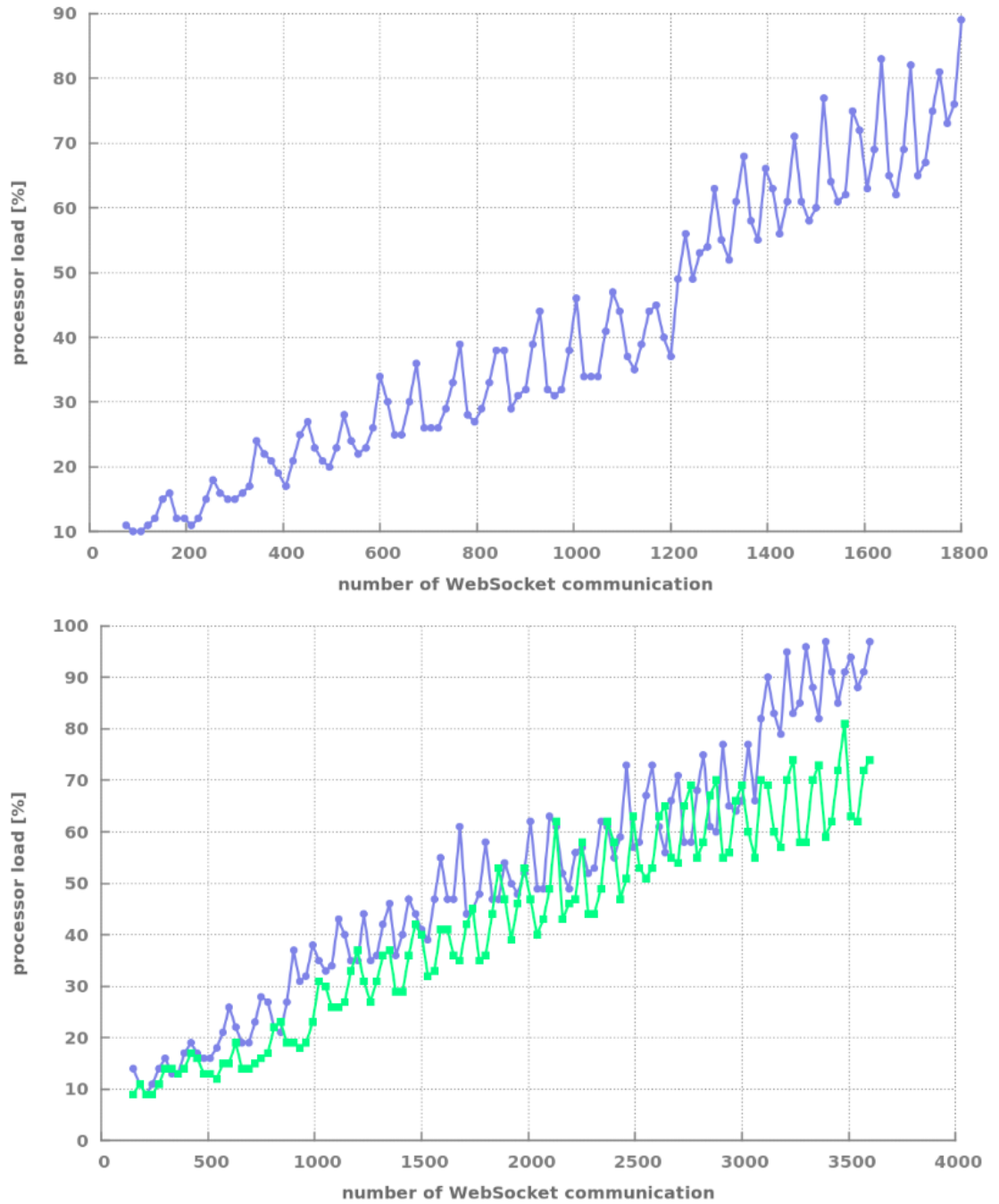


FIGURE 3.1: Client throughout

From Figure 3.1 it can be inferred that the client implementation works flawlessly. Adding a second core enables twice as much communication to be established.

### 3.1.2 browser testing

As mentioned in Appendix C.1, by operating minor changes in the `index.html` file, the browser can be configured to display in real time the number of pings received by a particular worker. If the experiment is running locally, typing `localhost:8080` in the url will link the browser to one worker.

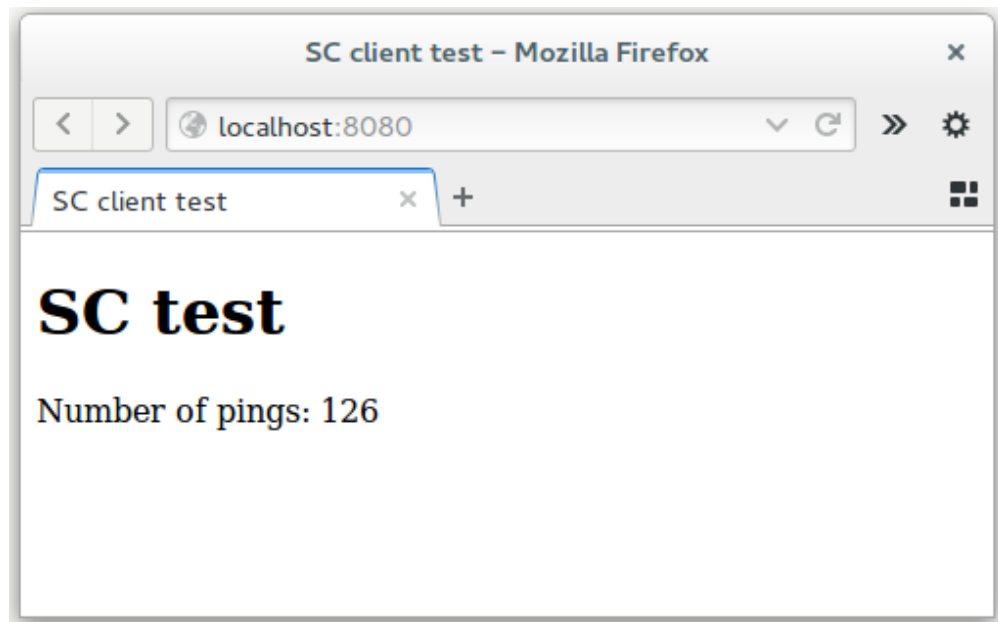


FIGURE 3.2: Browser connection to SocketCluster

By doing so we can embody a user connected to our WebSocket server and have a better idea of the reactivity of the server.

## 3.2 Comparison with engine.io

SocketCluster has been created to ease the creation of multi-core WebSocket server. Logically the first experiment carried out on the server was to compare a WebSocket to a traditional Engine.io server.

Engine.io and SocketCluster codes can be found in Appendix A and B.

Parameters	
Instance type	amazon ec2 m3.2xlarge
Experiment time	60 s
Number of new communication created at each iteration	20
Client creation period	1 s
Type of ping	random number
Ping period	2.5 s
Number of clients	2

### SocketCluster implementation

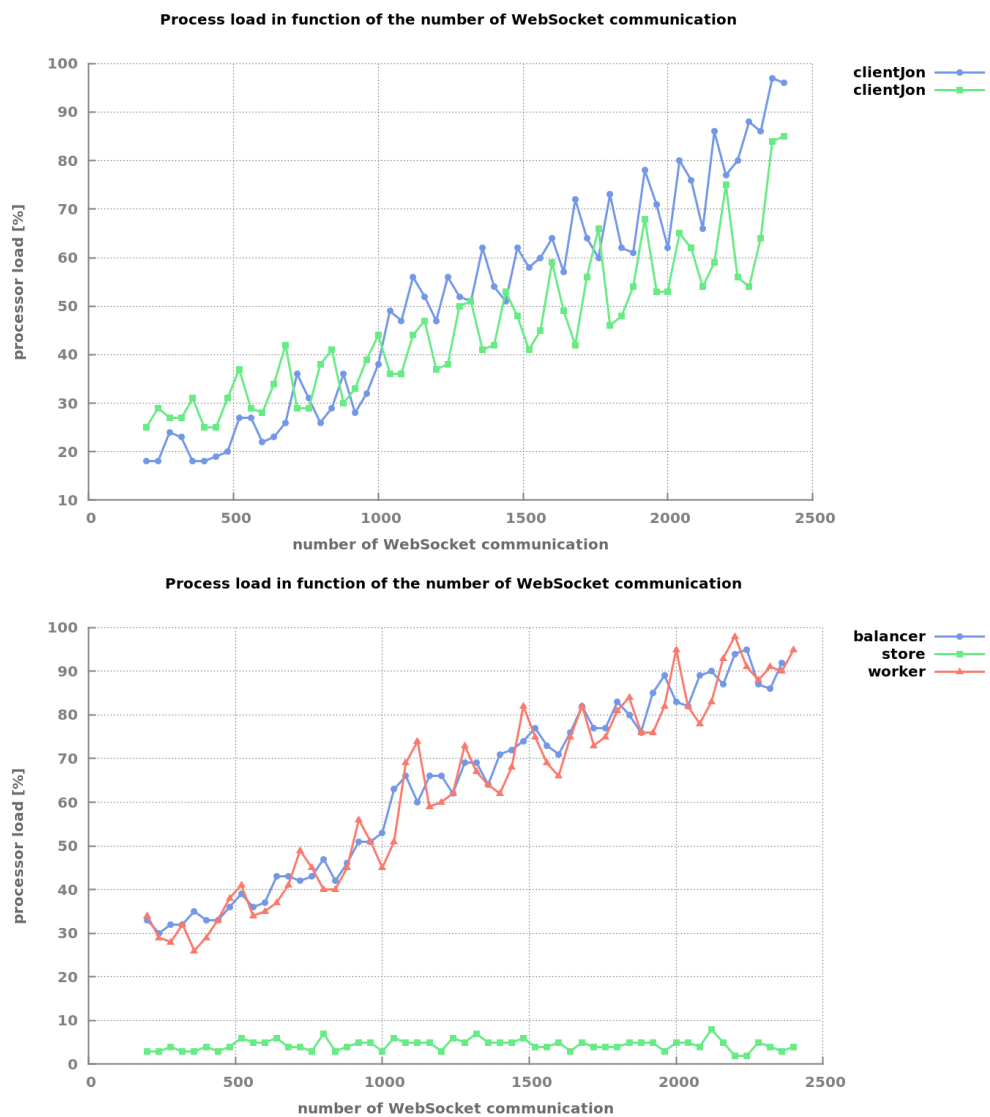


FIGURE 3.3: WebSocket implementation



In this experience, two clients are used to achieve a maximum of 2400 WebSocket communications. The server was configured to use one storage, one load balancer and one worker. While the store processor is quite idle, the two other processors on the other hand are almost used at full capacity.

### Engine.io implementation

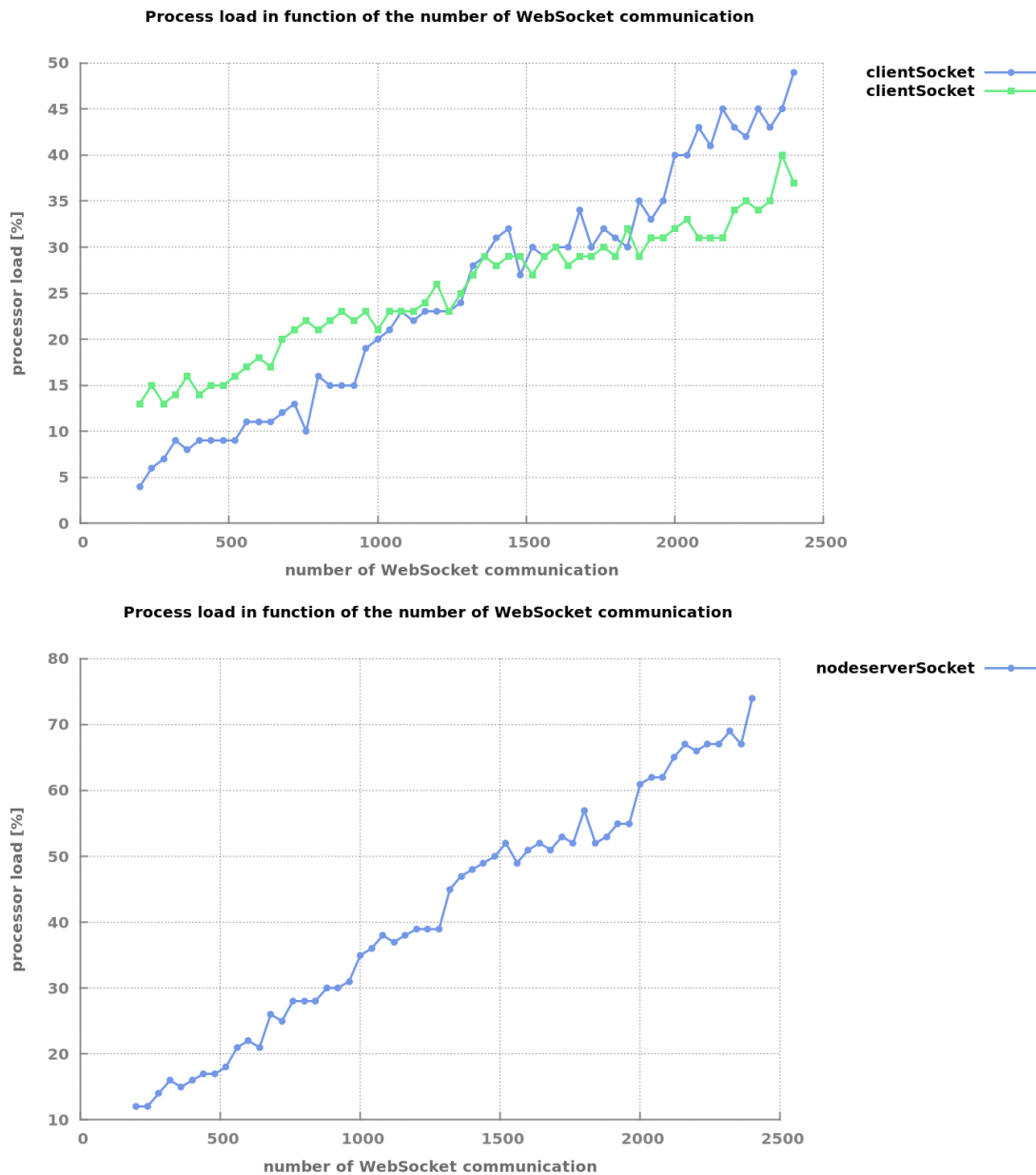


FIGURE 3.4: Engine.io implementation

Surprisingly, pure engine.io implementation seems to be more efficient. Clients are hitting a maximum of 50% processor usage compared to 90% for WebSockets.

On the server side, engine.io processor peaks at 75% compared to almost 100% for WebSockets. Also even if both code have been deployed on similar virtual machines: **amazon ec2 m3.2xlarge** the engine.io server is running only on one core compared to three for SocketCluster (one storage, one load balancer and one worker). This seems to show, SocketCluster is not adapted to low number of communication.

An interesting study worth doing at this point, is to try to use SocketCluster on one core.

### 3.3 SocketCluster context switching

For this experiment a single core virtual machine is used for the server: **amazon ec2 m3.medium**.

Parameters	
Server instance type	amazon ec2 m3.medium
Client instance type	amazon ec2 m3.2xlarge
Experiment time	80 s
Number of new communication created at each iteration	40
Client creation period	1 s
Type of ping	random number
Ping period	2.5 s
Number of clients	2



FIGURE 3.5: Context switching

At first glimpse, anyone can immediately tell there is a problem with the server graph. The Load seems to vary randomly at an average of 40%. What really happens, is that most WebSocket connections are dropped shortly after being created or they not are even created. The problem is a single core needs to handle four threads. So each time another application is called the context changes. The result is even worse in the case of a multi-processor server, because threads are then balanced between processors. Threads are heavy weight units, moving them introduces consequent overheads.

In conclusion, this experiment proves SocketCluster is not aimed to be used with project which involve more threads than available cores.

### 3.4 Horizontal scaling of SocketCluster

This section evaluates the performances of SocketCluster for a growing number of processors.

#### Client code

The client code used in all this part is the same. Two clients are used to produce a maximum of 2400 WebSocket communications.

Parameters	
Instance type	amazon ec2 m3.2xlarge
Experiment time	60 s
Number of new communication created at each iteration	20
Client creation period	1 s
Type of ping	random number
Ping period	2.5 s
Number of clients	2

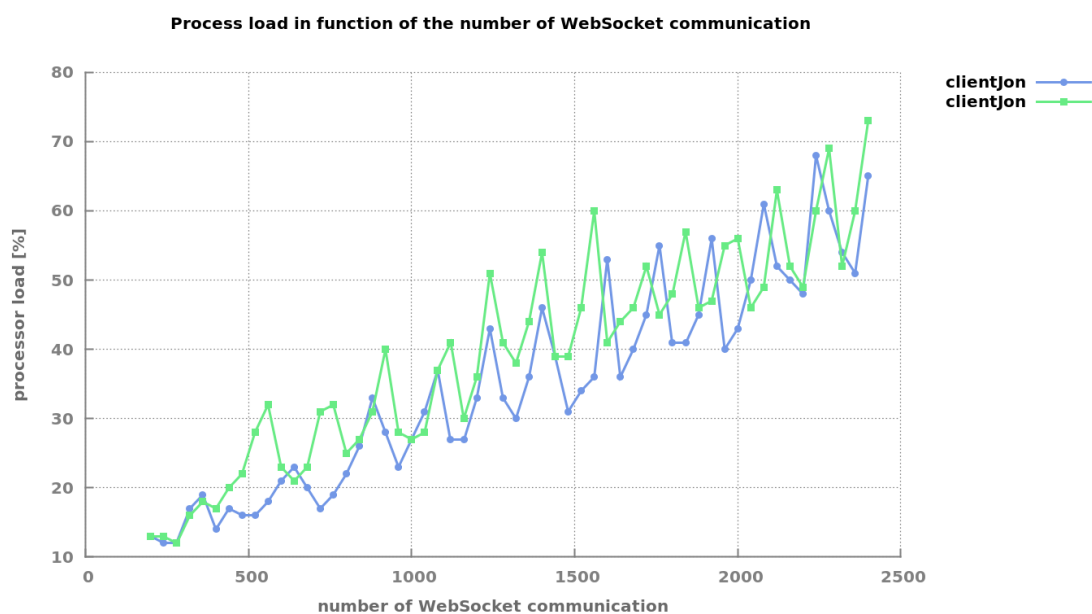


FIGURE 3.6: client code

### Experiment on three cores

The first test is run a server using a one store, one load balancer and one worker.

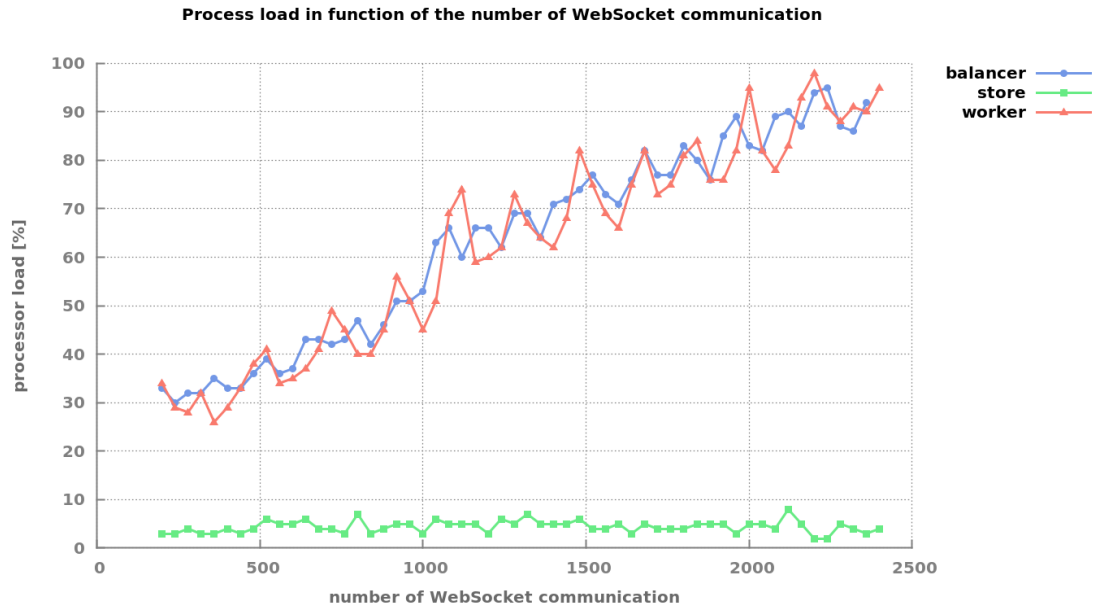


FIGURE 3.7: Server with three cores

Figure 3.7 clearly shows the worker and load balancer cores are almost used to their full extent. In order to handle more communication more cores should be added.

### Experiment on five cores

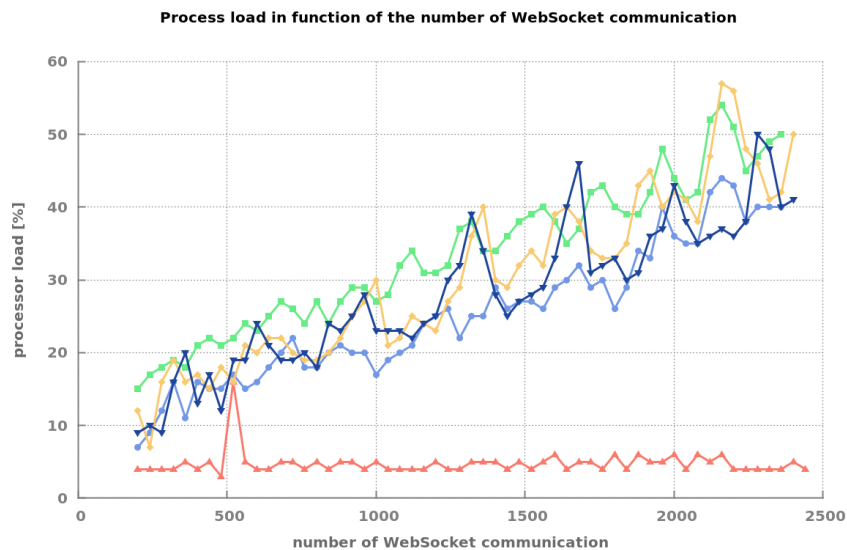


FIGURE 3.8: server with five cores

In this experiment two more cores have been added. Load balancers and workers nicely balance the work between themselves and the maximum load drops to 50%.

### Experiment on seven cores

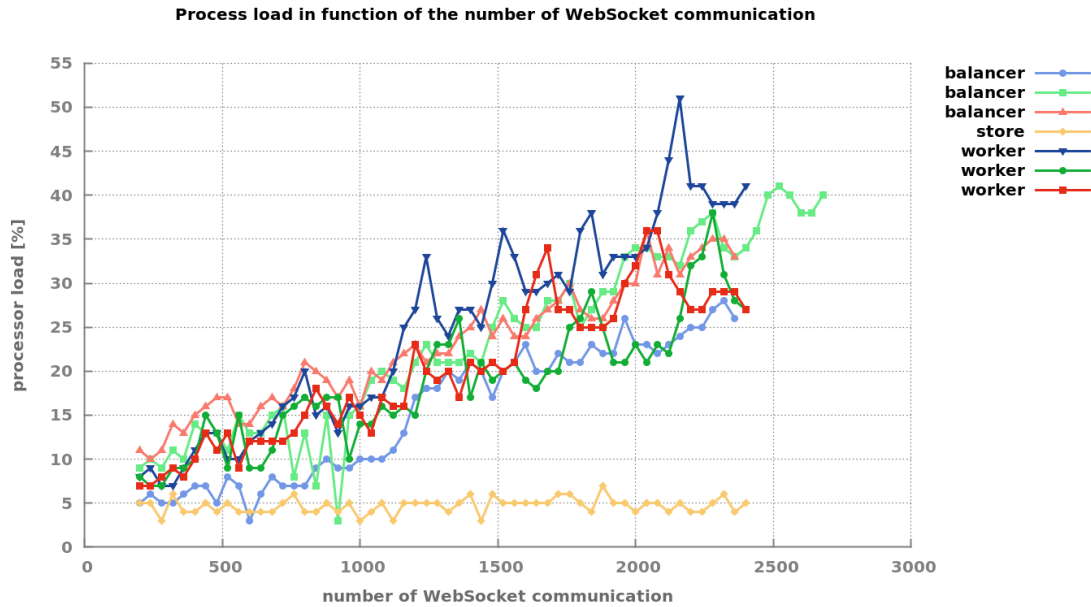


FIGURE 3.9: server with seven cores

This last test is less conclusive. With a total of 3 cores for load balancers and three for workers the processors load varies between 30% and 50% depending on the task.

As expected, in the long run by adding more processor SocketCluster's performance get better then engine.io. However in case n is the number of available processor, SocketCluster is not n times more effective then engine.io.

Actually in this experiment it seems that an equivalent number of workers and load balancers are needed for the application to run seamlessly. In case the application doesn't use a store, to gain twice as much computational power, twice as many processor are required. This makes SocketCluster  $\frac{n}{2}$  time more efficient than engine.io.

Furthermore, it showed adding too many cores is a waste of resources. This stresses the importance of finding a load balancer/worker/store ratio rule.

### 3.5 Parameters' influence

This section aims at determining which parameter between the number of WebSocket communications, the period of the pings and the size of the message exchanged has the most influence on the server processor usage.

The library `delivery` has been used to transfer file over WebSocket. The code can be found in Appendix A.4.

Fixed parameters	
Instance type	amazon ec2 m3.2xlarge
Experiment time	60 s
Number of new communication created at each iteration	20
Client creation period	1 s
Type of ping	random number

## Reference experiment

This first experience will be taken as a reference for the next ones. It has been carried out with 2 clients establishing together a total of 2400 communications. The period of the pings is in average four seconds and the size of the file exchanged is 81 bytes.

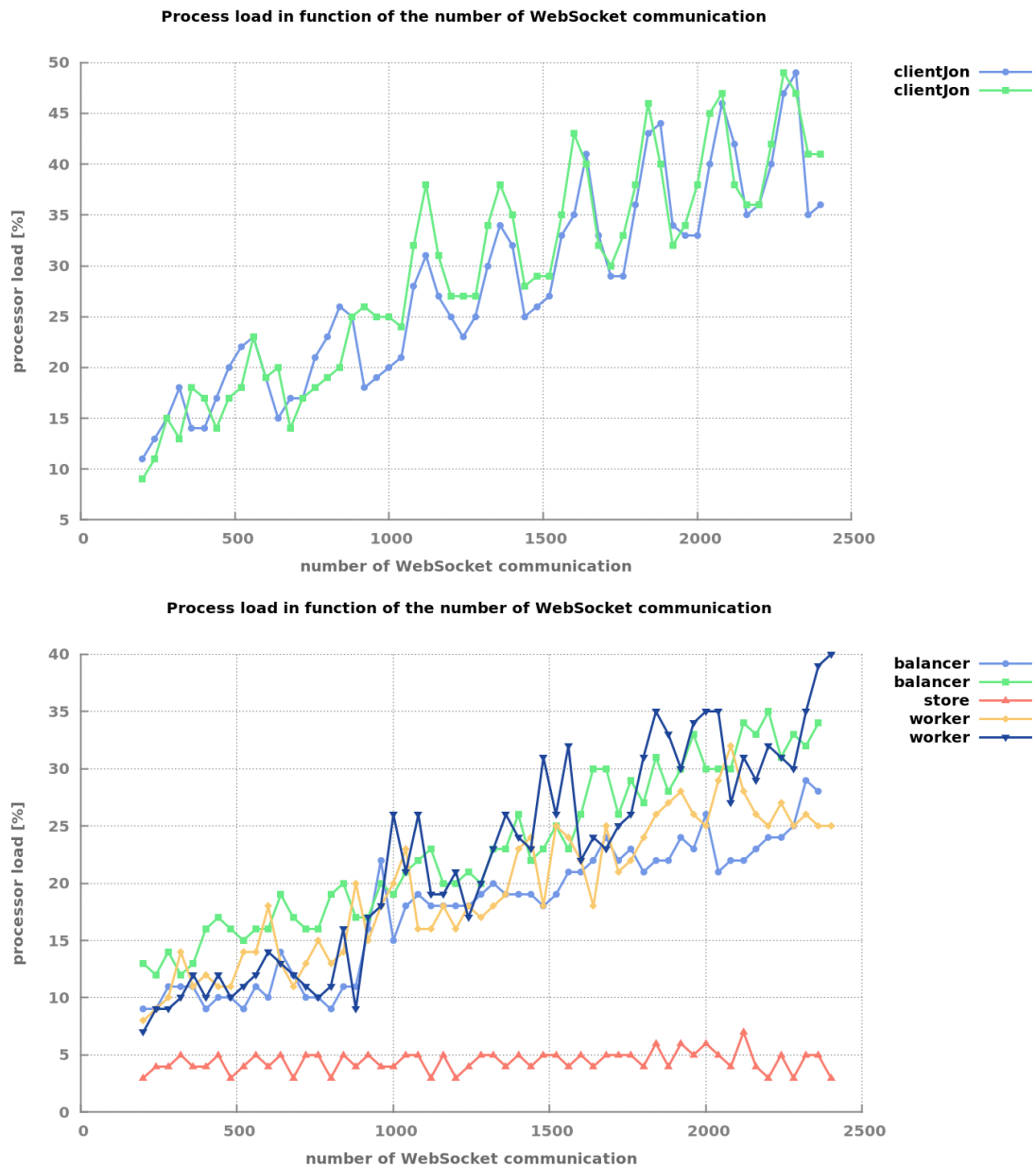


FIGURE 3.10: Reference experiment



### Pings' period experiment

In this experiment, the average time separating two pings has been decreased from four to three seconds.

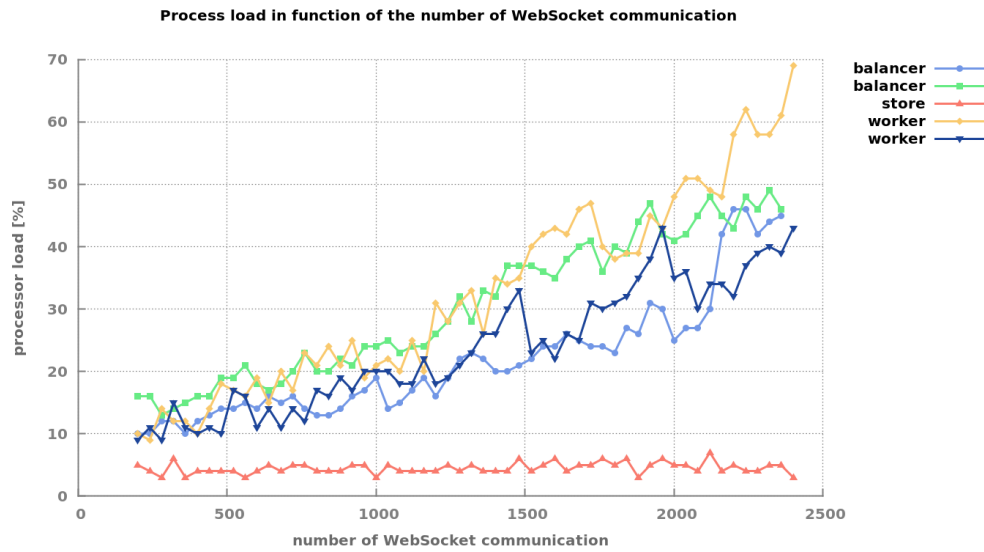


FIGURE 3.11: Pings' period experiment

### Amount of WebSocket communication experiment

The following Figure stresses the influence of the number of WebSocket communication channel. To obtain more communication, a third client has been added compared to the reference experience 3.10.

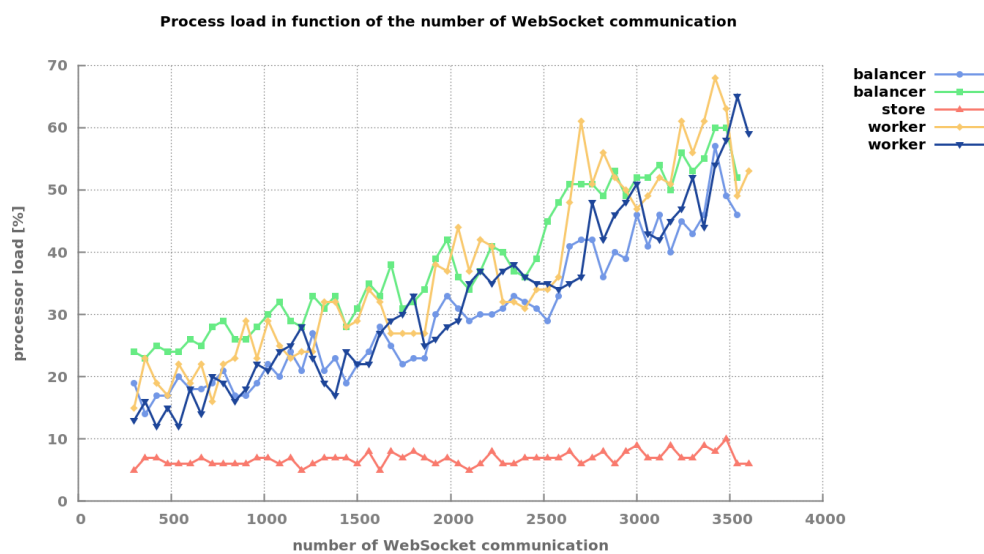


FIGURE 3.12: Amount of WebSocket communication experiment

### Size of exchanged files experiment

This last graph underlines the influence of the size of files. The file transferred in this experiment is 500 kbytes compared to 1 kbytes for the reference experience.

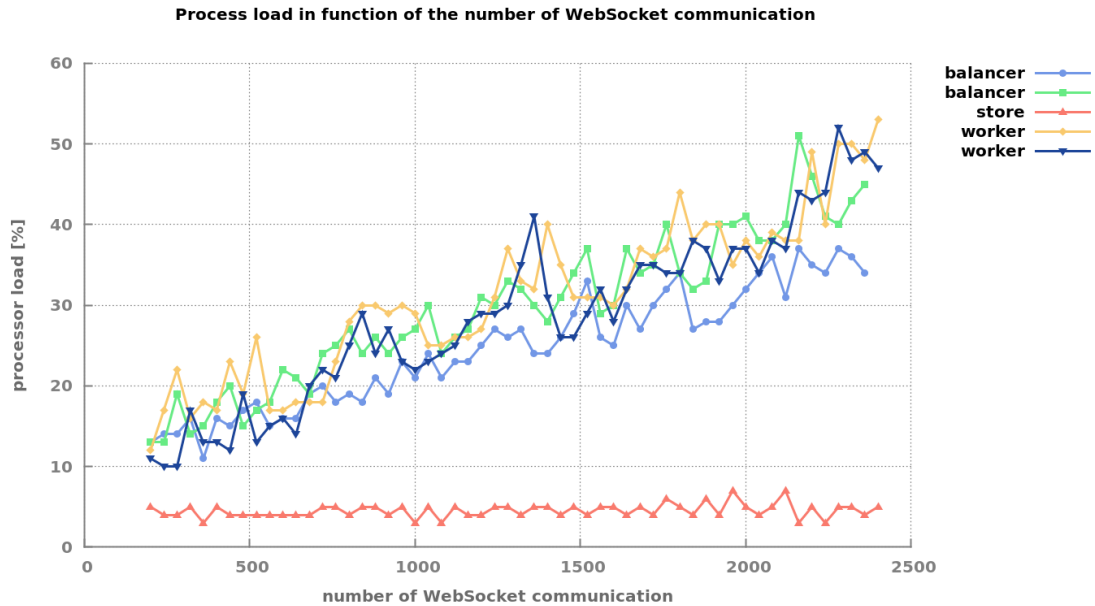


FIGURE 3.13: File size experiment

In conclusion, it seems that the size of the exchanged files isn't as important as the rate of pings and the number of WebSockets communications.

## 3.6 Concurrent connections experiment

This study was done to investigate the number of connections a single server can handle. As seen in the previous section, the number of connections is tightly bound to the parameters used to simulated the clients interactions with the server. Lets suppose each client receives a small file from the server every 2.5 seconds in average.

Parameters	
Server instance type	amazon ec2 c3.8xlarge
Client instance type	amazon ec2 c3.4xlarge
Experiment time	150 s
Number of new communication created at each iteration	10
Client creation period	1 s
Ping period	6 s
Size of the file exchanged	small

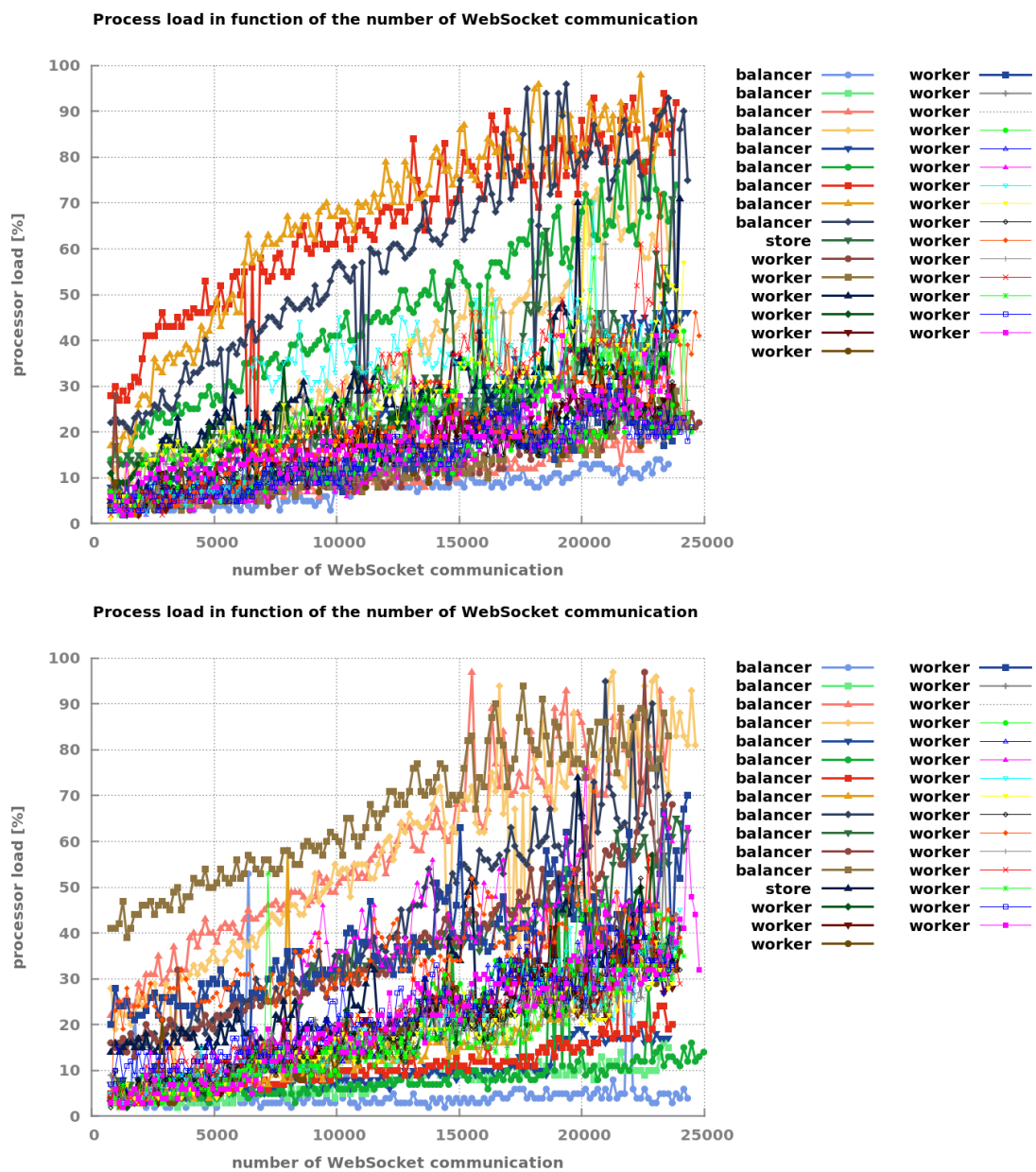


FIGURE 3.14: Maximum number of WebSocket communication

This experiment has been carried out on the biggest server made available by amazon ec2. SocketCluster will hardly be used in this conditions during normal usages. It is way cheaper to make clusters of SocketClusters server then to use a beastly server like this one.

This experiment confirmed SocketCluster is able to support around 25 000 concurrent connections. It also pointed out an imperfection of SocketCluster. The first graph is an experiment with 9 load balancers and 21 workers. The second with 12 load balancers and 18 workers. In the first experiment the load balancers' load is quite high. Adding more communication will result in communication to be dropped, as a result the second experiment has been carried out with more load balancers. But the previous figures clearly show that some load balancer are still using way too much computing power and some on the other hand are almost idle.

This points out a bad load balancing between the load balancers themselves.

### 3.7 Experiment summary

The client throughout tests showed the number of communications are scaling linearly when adding more cores. It also gave an insight into the user experience when using SocketCluster.

The second section was a little disappointing, one would expect a SocketCluster code running on three cores to achieve better then a regular engine.io code running on one core. However it is not the case, engine.io is significantly better.

The third section stresses the importance of running SocketCluster on a less processus then available cores. Otherwise the operating system as to operate heavy weight context switching.

The forth section studies the horizontal scaling of SocketCluster. Apparently, in a relatively low parallel environment, the application needs as much load-balancers as worker. And once they get saturated, adding a load-balancer and a worker will efficiently increase the performances.

The fifth experiment demonstrated the number of communication and the periods of pings increase the processor usage more quickly than the size of the messages exchanged.

The last experiment which was intended as a pure concurrent experiment, proved SocketCluster can handle 25k communications on a single server. But more importantly it showed that in a highly parallel environment, the load balancers begin to miss behave.

# Chapter 4

## Conclusion

After studying the current research around WebSocket in a distributed environment, this thesis focused on benchmarking of the node.js's real time engine SocketCluster.

SocketCluster is a promising library still actively under development. it efficiently provides a highly scalable WebSocket server that makes use of all available cpu cores on an instance. it removes the limitation of having to run node.js code on single cores.

### **Experiment conclusion**

Experiments carried out on SocketCluster revealed two main limitations. If running on comparable hardware, a SocketCluster worker will be less efficient then a basic engine.io implementation. Also SocketCluster efficiency dramatically drops if it is run with more process then available cores because of context switching.

SocketCluster should be used in highly parallel environment and therefore these limitations rarely apply. SocketCluster theoretically enables user to scale an application vertically without limits. N being the number of cores the server has, SocketCluster has been proved to be at least  $\frac{N}{2}$  more efficient then a basic node.js implementation. As the number of cores rises, it looks like the performance could be slightly better then  $\frac{N}{2}$ . The load balancers begins to misbehave and performance is limited by a few overloaded load balancers. However, it is probably only a question of time until a patch fixes this issue.

**Future work**

While benchmarking SocketCluster, useful SocketCluster features were considered. System administrators could benefit from a real-time monitoring tool to check the state of each threads and thus help them manage the size of the cluster. The monitoring tool could even be linked with an algorithm to automatically append or delete threads. SocketCluster would then be an autonom entity. Scaling on its own without any human interaction.

Also further studies could be carried on SocketCluster on more then on server. Since each cores already operates as a separate thread, the perforance shouldn't decrease if spread on many servers. But it might be worth checking.

# Appendix A

## SocketCluster

### A.1 Simple ping-pong exchange

#### Client code

This is an example of a WebSocket client code spread on all available cores. New clients are spawned every `numberClientsEachSecond`. Thereafter, every `intv` each clients sends a ping event cast to a Javascript JSON object.

```
if (cluster.isMaster) {
  for (var i = 0; i < numProcs; i++) {
    var worker = cluster.fork();
  }
} else {
  var count = 0;
  var connectSC = function () {
    var options = {
      protocol: 'http',
      hostname: hostname,
      port: "8080",
      autoReconnect: true
    };

    var socket = clientSC.connect(options);

    // SENDS PINGS
    var intv = Math.round(Math.random() * 5000);
    setInterval(function () {
      socket.emit('ping', {param: 'pong'});
    }, intv);

    // CREATION OF NEW CLIENTS
    setTimeout(connectSC, 1000/numberClientsEachSecond);
  };
  connectSC();
}
```

FIGURE A.1: Pings from client



To best simulate clients interaction with a websocket server, new sockets are created at random intervals `intv = Math.round(Math.random()*5000)`.

### Server code

The server listens for pings event and answers back with pongs event. In this case the pong event is an integer counting the number of pings this particular worker had during the whole experiment.

```
// Handles incoming WebSocket connections and listens for events
wsServer.on("connection", function (socket) {

  // The server listens to the ping event from the clients
  socket.on("ping", function (N) {

    // Sends simple pong event
    socket.emit('pong', ++count);
  });
});
```

FIGURE A.2: Server answering with pongs

## A.2 File transfer

### Client code

In this example, the goal is to exchange a file using the WebSocket protocol. For this purpose, the node.js `delivery` library is used.

New clients are created on the same model as the previous example. Each new client is stored in the `clients` array. Each clients are also periodically sending pings. The only add on is the `map` function to enable the each socket to retrieve the document sent by the server.

```

var dl = require('delivery');

clients.map(function(client){

  // RECEPTION OF FILES
  var delivery = dl.listen(socket);
  delivery.on('receive.success',function(file){
    fs.writeFile(file.name, file.buffer, function(err){
      if(err){
        console.log('File could not be saved: ' + err);
      }else{
        console.log('File ' + file.name + " saved");
      }
    });
  });
});

```

FIGURE A.3: Clients receptionning files

### Server code

The server listens for pings. And sends back a file, `foo.txt` in this example.

```

var dl = require('delivery');

// Handles incoming WebSocket connections and listens for events
wsServer.on("connection", function (socket) {

  // The server listens to the ping event from the clients
  socket.on("ping", function (N) {
    var delivery = dl.listen(socket);
    delivery.connect();
    delivery.on('delivery.connect',function(delivery){

      delivery.send({
        name: 'foo.txt',
        path : './foo.txt'
      });

      delivery.on('send.success',function(file){
        console.log('File successfully sent to client!');
      });
    });
  });
});

```

FIGURE A.4: Server sending files

# Appendix B

## Engine.io

This appendix gives the code used to create a simple engine.io server and client. Comparison with SocketCluster code in appendix A shows the difference between both implementation is small.

In fairness, SocketCluster API is very close to engine.io.

### Client code

```
var cluster = require('cluster');

if (cluster.isMaster) {
  for (var i = 0; i < numProcs; i++) {
    var worker = cluster.fork();
  }
} else {
  var connectSocket = function () {
    var destination = 'http://' + hostname + ':8080';
    var socket = require('socket.io-client')(destination);
    var intv = Math.round(Math.random() * 5000);

    // SENDS PINGS
    setInterval(function () {
      socket.emit('ping', {param: 'pong'});
    }, intv);
    setTimeout(connectSocket, 1000/numberOfClientsEachSecond);
  };
  connectSocket();
}
```

FIGURE B.1: Pings from client

## Server code

```
var app = require('http').createServer(handler)
var io = require('socket.io')(app);
var count = 0;

app.listen(8080);

io.on('connection', function (socket) {
  socket.on('ping', function(N){
    socket.emit('pong', ++count);
  })
});
```

FIGURE B.2: Server answering with pongs

# Appendix C

## Real time throughout check

By inserting the following script in `index.html` the browser will display in real-time the number of pings received by a WebSocket server.

```
<script type="text/javascript">
  var options = {
    protocol: 'http',
    hostname: "localhost",
    port: "8080",
    autoReconnect: true
  };
  var socket = socketCluster.connect(options);
  socket.on('connect', function () {
    console.log('CONNECTED');
  });
  socket.on('pong', function(data){
    console.log(data);
    var curHTML = document.body.innerHTML;
    curHTML += 'Number of pings: ' + data + '<br />';
    document.body.innerHTML = curHTML;
  });
  socket.emit('ping');
</script>
```

FIGURE C.1: Modification to `index.html`

All it does is emitting a ping, then listening to the pong event and displaying it directly in the html page. The pong payload as can be seen in A.2 is `count`, an integer incremented each new ping.

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