WebSocket and the Real-Time Web

A Comparison…..

Contents

Abstract

Text

List of Figures

Text

Preface

Text

Acknowledgements

Text

1 Introduction

1.1 Motivation: Real-Time Web

To understand what is meant by the term real-time in this thesis, consider the following example. We have a chat room application where several clients are connected to a centralized server. The server listens for messages from the clients and as soon as one client sends a message to the server, the server immediately broadcasts the message to all other connected clients. This immediate handling of new data on the server, as well as a bidirectional pipe that makes it possible, is what real-time means in this thesis. In fact, this example is very similar to one of the methods used in the project part later.

For many types of applications having this sort of real-time behavior is crucial. For systems where uptime is critical, health related systems for example, real-time error message delivery can be a matter of life and death.

As will be emphasized in the background part of this thesis, the web is inherently not designed for real-time, as HTTP, the protocol powering the web, is unidirectional and request-response oriented. However, with HTML5, the W3C finally brings native ways to build real-time apps for the web. WebSockets and Server Sent Events are the technologies that will be explored in this thesis.

1.2 Problem statements

Forventninger og introduksjon

Does WebSocket perform and scale better than traditional HTTP methods for real-time server-push?

When we want to achieve real-time behavior in our web app, how well does WebSockets really scale? Is there a significant difference to HTTP Long Polling and Server Sent Events? Metrics that come into play here; server CPU load, memory footprint and network usage.

Under what load levels does WebSocket break? Is this level higher than for HTTP Long Polling or Server Sent Events?

How far can we push WebSockets before we see a significant drop in response time from the server. Then compare this to the break point for HTTP Long Polling and Server Sent Events. Is there a significant difference? Most interesting metric here is the number of messages the server can handle per second.

Does client-to-server WebSocket messages perform and scale better than HTTP POST requests?

One of the powers of WebSockets is the ability to push messages both from the server to client and client to server. Although HTTP POST messages are similar to WebSocket client to server messages, it is interesting to find out how much better, if better at all, WebSockets

scale compare to HTTP with client-to-server messages. Metrics that come into play here are; server CPU load and memory footprint, network usage and most important - response time.

Stress test client-to-server messages to find out the load levels when WebSocket break.

Under what levels of load does WebSocket and HTTP POST messages start to show large deviation in response time? Does WebSocket provide better scaling capabilities compare to HTTP? Interesting metric here is number of messages per second the server can handle.

1.3 Related Work

Not so much. WebSockets are quite new.
Kristian
Joevik

Kristian Johannesen

1.4 Terminology

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Transports	Protocol on the transport layer. In this thesis it's used in context with either WebSocket, Server Sent Events or HTTP Long Polling

1.5 List of Acronyms

AJAX / Ajax	Asynchronous JavaScript and XML
DOM	Document Object Model
HTTP	Hypertext Transfer Protocol
JSON	JavaScript Object Notation
SSE	Server Sent Events
TCP	Transmission Control Protocol
W3C	World Wide Web Consortium
WS	WebSocket
XML	Extensible Markup Language

1.6 Code

Link to github

1.7 Outline

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2 Background

2.1 Introduction to Real-Time Web

Tim Berners-Lee understood the potential of networked computers when he invented the World Wide Web in 1991, but he cannot have had any idea of the impact his invention would have on the world. Today, at the age of only 23 years, the web is hard imagining living without. It's remarkable how quickly the technology has merged itself into the society, even for non-tech-savvy people. We do everything from reading news and paying bills to social interaction and playing games on the web. Even though the web is just a subset of the internet, many people today don't know the distinction.

The web was originally designed to fetch static, non-styled, text-only documents. Over time stylesheets and script files were added and today the web mainly consists of these three components:

- HTML - An XML like markup language that describes a website's content.
- CSS - A language that describe styling attributes of HTML components.
- JavaScript - The web's programming language.

The web still works around the basic principle of document fetching, but the "documents" retrieved by a web browser can be highly complex and interactive applications, with Google Maps as an great example. Even though Google Maps seems to be completely different from simple websites such as blogs or newspapers, they are both powered by the same technologies underneath. Today it's very likely that a bunch of the apps on your own smartphone are powered by HTML, CSS and JavaScript as a web app running locally on your device. This shows how far these web technologies has come.

There is however one area where the web has lagged far behind platform native applications - the networking protocols. Along with HTML came HTTP, the protocol designed to retrieve HTML documents. HTTP works great for simple document fetching but is not designed for the advanced use cases of todays web apps. As will be revealed in this thesis, it is hard and suboptimal to develop real-time apps using HTTP.

As mentioned earlier, HTML5 intends to improve web transports with Server Sent Events and WebSocket. Server Sent Event extends HTTP and gives the ability to push data natively from the server. WebSocket is a totally new protocol set out to solve most of HTTP's limitations compared to TCP.

Following in the background part of this thesis, is a presentation of HTTP, Server Sent Events and WebSocket. This will form a good foundation for understanding what comes later in the thesis.

2.2 HTTP

HTTP is an application level network protocol used to deliver data from a server to a client. The original definition of HTTP was written in 1991 by Tim Berners-Lee, shortly after he invented the Web at the physics institute in CERN. The web was intended as a platform in which researchers at CERN could easily share and access each others documents. HTTP was originally designed to be a very simple protocol with just one purpose, to fetch (or GET) documents. The basic principle behind HTTP is therefore just a single request sent from the client to the server and the single requested document sent back as a response. There wasn't any need for storing information about the clients on the server side, so the protocol was designed as a stateless protocol. Every connection is treated the same way.

The whole request is sent as plain ASCII text and consists of a GET followed by the document's address. The server parses the GET request and sends the the requested document back as a response. The server terminates the underlying TCP connection when the document is sent.

```
GET /index.html HTTP/1.0
Host: www.uio.no
<blank line>
```

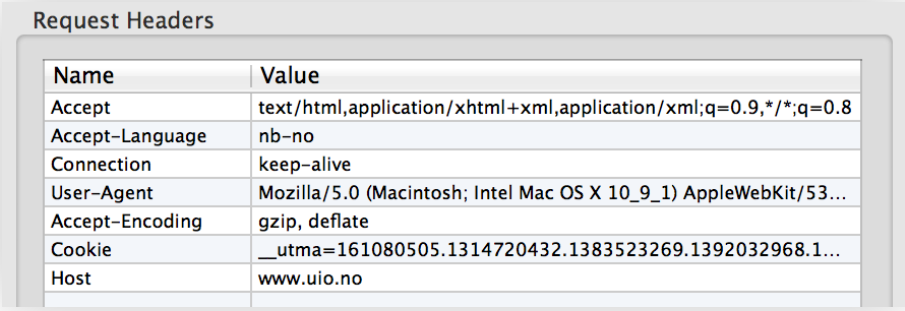
Figure 1: A GET request to www.uio.no. The blank line indicates end of message.

The HTTP description above is a brief run through of Tim Berners-Lee own words about version 0.9 of the protocol, from 1991[1].

The web's potential, also outside of the research world, was clearly huge and on the 30th of April 1993, it was decided that the web was to be «freely usable by anyone, with no fees being payable to CERN»[2]. A year later, in October 1994, The W3C (World Wide Web Consortium) was formed as the main standards body for the Web and to this day Sir Tim Berners-Lee is still the director. In 1996 the W3C introduced the finalized version of the protocol, HTTP/1.0. Version 1.0 added two methods to the already existing GET method - POST and HEAD. POST is used in conjunction with web forms and used when a user wants to submit data to the server, and HEAD is used as a GET where you don't want the actual response data, but only the response *header fields*.

Header fields are an important part of HTTP. The header fields are meta data that are added into the HTTP requests and responses. The «Host» line in figure 1 above is the Host header field. Headers are there for the server and client to tell the other part a bit about themselves. As an example, it's useful for the server to know what kind of language the client wants the requested document in.

The image below shows the entire GET request my web browser initiated when going to www.uio.no, with the browser adding several header fields:



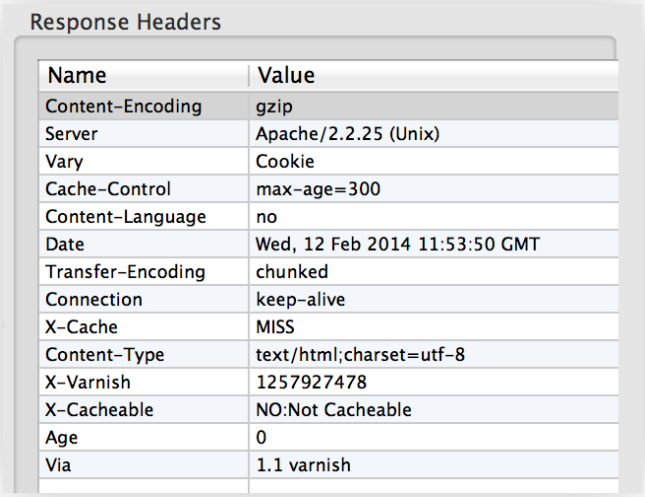
Request Headers

Name	Value
Accept	text/html,application/xhtml+xml,application/xml;q=0.9,*/*;q=0.8
Accept-Language	nb-no
Connection	keep-alive
User-Agent	Mozilla/5.0 (Macintosh; Intel Mac OS X 10_9_1) AppleWebKit/53...
Accept-Encoding	gzip, deflate
Cookie	__utma=161080505.1314720432.1383523269.1392032968.1...
Host	www.uio.no

Figure 2: HTTP GET request to www.uio.no. Captured using HTTPScoop[3].

As you can see above, there's a significant number of header fields. For example, the User-Agent field tells the server what kind of computer, OS and web browser the client is running on, while the Accept header tells the server what files the client web browser can read. HTTP Headers are an important part of the protocol and adds a marginal degree of state.

The server responds to the request with a HTTP response. The response embody header fields followed by the HTML code. As the web browser parses and renders the HTML file from top to bottom it may find link, script and image tags inside the markup. This means that the website consists of more elements and the client must request those as well. As an example, for http://www.uio.no there was a total of 56 files (JavaScript, CSS and image files) to be fetched, resulting in 56 GET requests and 56 server responses. Most files on the website change only occasionally, so chances are that your browser has cached most of a site's content, so that the next time you visit, the number of necessary GET requests are way lower. Below is an example of a server response with its headers:



Response Headers

Name	Value
Content-Encoding	gzip
Server	Apache/2.2.25 (Unix)
Vary	Cookie
Cache-Control	max-age=300
Content-Language	no
Date	Wed, 12 Feb 2014 11:53:50 GMT
Transfer-Encoding	chunked
Connection	keep-alive
X-Cache	MISS
Content-Type	text/html;charset=utf-8
X-Varnish	1257927478
X-Cacheable	NO:Not Cacheable
Age	0
Via	1.1 varnish

Figure 3: HTTP GET response from www.uio.no. Captured using HTTPScoop.[3]

Considering that http://www.uio.no is a typical web site, it doesn't require much insight to realize that closing the underlying TCP connection after each server response is very inefficient. When HTTP/1.1 arrived in 1997 this issue was resolved by allowing the client to tell the web server to keep the lower level TCP connection open. This is done by providing the «Connection: keep-alive» header as seen in figure 2. Many years on, HTTP/1.1 is still the current version.

2.3 Ajax, HTML5 and Web Apps

As mentioned, HTTP was designed to serve static hyperlinked documents. Today however, you only sporadically visit a site that is static and pure HTML. Almost every site you visit are highly interactive and complex creations with lots of JavaScript code running in the background. This development started in the late 1990s with Microsoft Outlook, but skyrocketed after 2004 with Google Gmail and Google Maps. These types of websites started to behave more like platform native applications and was a clear departure of the hyperlinked documents that the web originally consisted of. Terms like *Web Applications* and *Single-Page Apps* came forth, and with websites going more complex and JavaScript heavy, having a fast web browser was a clear advantage. This lead to a great race between Microsoft, Google, Mozilla and Apple to build the greatest JavaScript engines. Today they are lightning fast.

But, how could developers build these Web Apps with the limitations the web forced upon them? Central to this development was Ajax, a technique for fetching data in the background using JavaScript and HTML5.

2.3.1 HTML5

HTML5 is the fifth revision of the HTML markup language and the first major update since HTML4 was standardized in 1997[4]. Even though HTML5 adoption stated many years ago, the W3C recommendation was just recently finalized[5]. HTML5 is, despite its name, much more than just an updated HTML version. It's a collection of many technologies that's intended to clean up the syntax and unify web technologies as well as introduce new APIs that makes the web a platform for full fledged applications.

The new features include:

- Several new HTML markup tags, including audio, video, canvas and svg tags for native, audio, video, 2D graphic and vector graphic support respectively.
- Version 3 of the CSS styling language with support for animations, 2D and 3D transitions, media queries to support multiple screen sizes and more.
- New JavaScript APIs that include support for Geolocation, Camera, Microphone, Offline apps, Web Storage, Server Sent Events and WebSockets.

Prior to HTML5, accessing a device's hardware, like camera, microphone or GPS was not possible without proprietary web plugins, like Adobe Flash. With HTML5 it's possible to build applications that resemble their platform native counterpart, right in the browser. With tools like PhoneGap[6] and Cordova[7], it's possible to take it one step further and package web apps to run along side native applications on the targeted device. As touched upon earlier, a great deal of mobile apps today are really web apps running in a WebView (an embedded web browser window) packaged by Cordova or PhoneGap. With HTML5 the term *web apps* truly comes to life.

2.3.2 Ajax

Ajax as a term was introduced by Jesse James Garret in 2004, when he wrote "Ajax: A New Approach to Web Applications"[8]. In it he states that Ajax is "… several technologies, each flourishing in its own right, coming together in powerful new ways…". At the center of Ajax

is the *XMLHttpRequest* JavaScript API[9]. It is used to send and retrieve data from a server asynchronously, all using existing HTTP methods such as GET and POST. Previously, a web browser typically requested a whole website for each GET it sent. With Ajax, this server interaction happens in the background and the client side JavaScript updates the HTML view (DOM) with new data. Even though Ajax has XML in its name, the type of data are not limited to just XML; today JSON[10] is a widely used format for representing hierarchical key-value data, with less overhead compared to XML. A great example of an Ajax powered web app would be Google Maps. When you pan around the map, the JavaScript running in your browser initiates Ajax GET requests to the server, requesting data of the area you are now looking at. When new images and map data has arrived, JavaScript running in your browser updates the DOM.

Ajax is at the center of web apps, and it brought interactivity to an otherwise static web. Even though Ajax gave new possibilities, there was no going around that Ajax didn't solve HTTP's problems, only improved an otherwise unsatisfactory situation.

2.4 Real-Time HTTP

For many applications pushing data between server and client is essential. Let's say you have a web app displaying stock prices. Stock prices can change very often, many times per minute. As soon as the server receives a stock price update from the broker, it would be nice to push the update immediately to connected clients. Achieving this kind of push behavior is quite trivial for platform native applications since you can just set up a full duplex TCP socket and listen for updates. Even though HTTP utilizes TCP on the transport layer, HTTP itself is just half-duplex and there are no way for the server to push messages to the client. All server sent messages must be a response to a client sent request. So how come, web apps like Twitter and Facebook seems as though they have real time server push capability? The chat on Facebook seems to push messages immediately, right? Following are a set of techniques, that accomplishes server push using HTTP.

2.4.1 HTTP Polling

The first solution that comes to mind is having timer running in the client side JavaScript, that periodically polls the server for updates. If these requests are sent frequently enough, it could be *perceived* as real time. This approach is called *HTTP Polling* and is quite simple conceptually and easy to implement. HTTP Polling works ideally if you know exactly when the server updates its data and you can ask for new values directly after that update. This is however, rarely the case. Take a chat application as an example; you don't know when the one you're chatting with sends a message. This can vary from some seconds to even minutes if the message is long. Trying to find the perfect update request rate is really difficult and varies greatly from application to application. The worst case scenario is that you end up sending a lot of requests that return an empty response. This is undeniably not a great thing, as it congests the network with unnecessary messages.

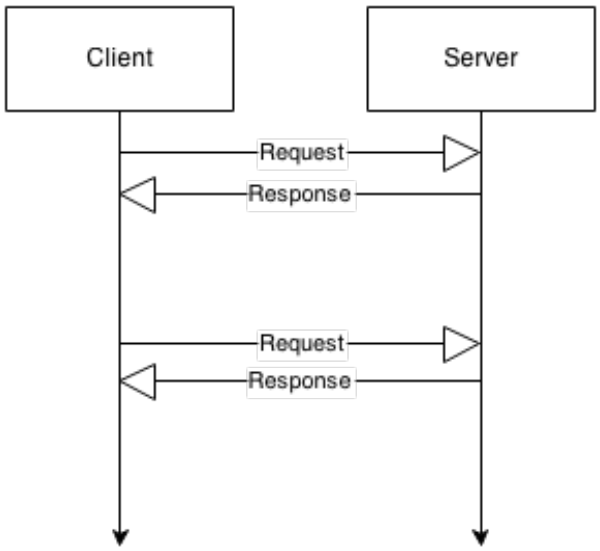


Figure 4: HTTP Polling example

2.4.2 Comet

When you need real time server push in you web app, HTTP Polling seems as a poor choice. Comet is an umbrella term for a set of programming models that achieve server push only using existing HTTP technologies. The two most used once are Long Polling and Streaming.

HTTP Long Polling

HTTP Long Polling is essentially the same as regular HTTP Polling except that the server delays the response until either new data is ready to be sent or a timer runs out. Immediately after response is received, the client sends a new server request and waits for new updates. As default the timer is 45 seconds[11]. Long Polling gives the user the impression of having data pushed from the server, even though it in theory is not.

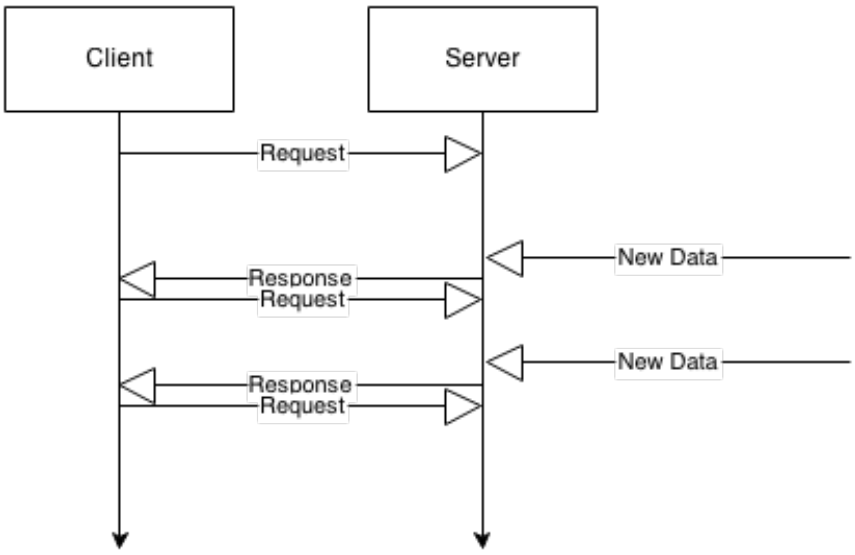


Figure 5: HTTP Long Polling Example

HTTP Streaming

HTTP Streaming, also known as «the forever-frame», is another practice that emulates server push. Chunked Encoding is a part of the HTTP/1.1 specification that lets the server start pushing chunked data to the client before the response size is known. A forever-frame is an HTML iframe that keeps receiving script tags as these chunks. These script tags are immediately executed on the client and the server can in practice keep this connection open as long as it wants.

2.4.3 Why Comet and HTTP is Unsatisfactory for Networking

So, if both Long Polling and Streaming seems to give web apps real time pushing of data, what is the problem? For HTTP Streaming, the biggest problem is the fact that it is very hard to debug and error check. With the server pushing scripts that are immediately executed on the client, debugging can be very tricky. Security is also a concern, as script tags are immediately executed. For HTTP Long Polling, consider our stock price web app from earlier, with clients now using Long Polling. In between the long polling timer runs out and a new request is sent from the client, a new price has arrived from the stock broker. Now the server must remember that this specific client has outdated information and push data as soon as the next polling request arrives. This adds complexity to an otherwise simple task.

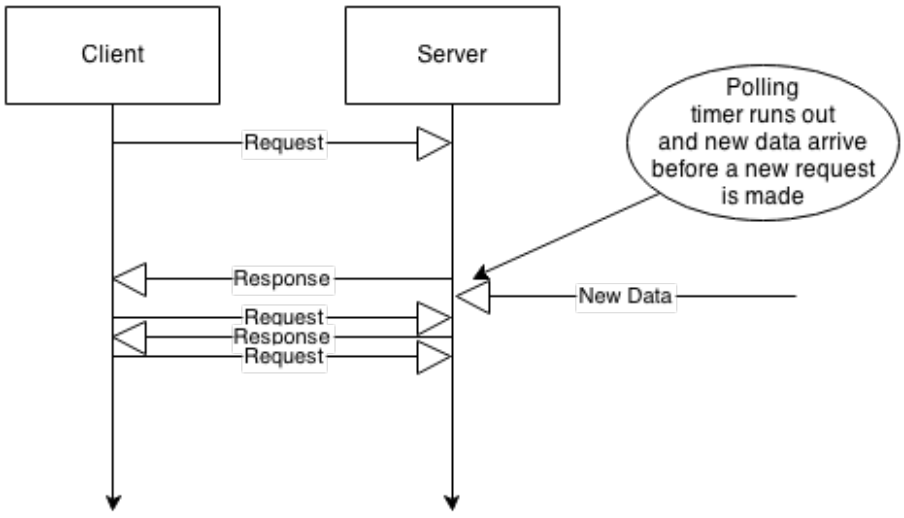


Figure 6: Example of client side outdated data with Long Polling

Long Polling also faces a problem when there are many updates of data and the client constantly has to reissue a polling connection. At this point Long Polling almost becomes regular Polling.

Another issue is related to HTTP headers. With my earlier GET example to www.uio.no, the amount of header data in all the requests are between *500 and 800 bytes*, and all 56 response headers are between *300 and 500 bytes*. For many real time applications where you want to send small messages, maybe just a couple of bytes, this wast amount of unnecessary header data is repeated for each packet and could cram the network.

Lastly, let's not forget that developers of native applications have had powerful full duplex TCP sockets forever. This is a feature web developers just doesn't have with HTTP.

Even though Long Polling and HTTP Streaming accomplishes push behavior, there are, as you have seen, several downsides to using the two techniques. Compared to the lower level more powerful TCP sockets, building real time networked applications for the web introduces many obstacles. Many types of real time applications that would benefit hugely from having a fast lower level TCP like protocol.

2.5 WebSocket

WebSocket is meant to be the TCP like protocol the web clearly needed to evolve as a rich application platform. It promise to be all about performance, simplicity, standards and HTML5[12] and is designed to work seamlessly together with HTTP. In order to understand what is unique to WebSocket and why it's important, we must dig into two parts of the technology; the protocol itself (RFC 6455[13]) and the API.

2.5.1 The WebSocket API

One of the great powers of WebSocket is its simple, yet powerful JavaScript API. The API was defined by the W3C and is the interface you interact with as a web developer. The following figure shows the entire interface.

```
[Constructor(DOMString url, optional (DOMString or DOMString[]) protocols)]
interface WebSocket : EventTarget {
        readonly attribute DOMString url;

        // ready state
        const unsigned short CONNECTING = 0;
        const unsigned short OPEN = 1;
        const unsigned short CLOSING = 2;
        const unsigned short CLOSED = 3;
        readonly attribute unsigned short readyState;
        readonly attribute unsigned long bufferedAmount;

        // networking
                        attribute EventHandler onopen;
                        attribute EventHandler onerror;
                        attribute EventHandler onclose;
        readonly attribute DOMString extensions;
        readonly attribute DOMString protocol;
        void close([Clamp] optional unsigned short code, optional DOMString reason);

        // messaging
                        attribute EventHandler onmessage;
                        attribute DOMString binaryType;
        void send(DOMString data);
        void send(Blob data);
        void send(ArrayBuffer data);
        void send(ArrayBufferView data);
};
```

Figure 7: The WebSocket API.

States

In contrast to HTTP, WebSockets are not stateless and the API lets us access a WebSocket's state with the attribute readyState. A socket can here have 4 different states during it's lifetime: *CONNECTING*, *OPEN*, *CLOSING* and *CLOSED*.

Events

WebSocket is an event driven protocol, meaning that there are certain events that trigger code to be executed. The API presents us with four events: *open*, *message*, *error* and *close*. The open event is fired as soon as a connection has been established with the server. «Message» is triggered when a new message has arrived. The error event is set off when an error has occurred and the close event is fired when the connection has been terminated.

```
var ws = new WebSocket('ws://example.com');
ws.onopen = function(e) {
      // Code to be executed once the connection is established
}
```

Figure 8: How to open a WebSocket connection to example.com and set up an open event trigger.

Methods

There are two methods you can call on a WebSocket object; *send* and *close*. «send» takes parameter data and sends it over the socket. A WebSocket accepts either String data or binary data, depending on you need. Since this is a new protocol, Strings are expected to be coded in UTF-8, removing all encoding problems. The «close» method is called when you want to terminate the connection. You can optionally provide a status code symbolizing the reason for the closing call and a reason string.

2.5.2 The WebSocket Protocol

With the API explained, it's time to look into the protocol itself. The WebSocket protocol was designed to work seamlessly together with HTTP. In fact, you have to already have an HTTP connection open before you initiate a WebSocket. When the HTTP connection is up, WebSocket uses a HTTP request's «Upgrade» header field to tell the server that it wants to upgrade from HTTP to WebSocket. This is all done over the same ports as HTTP to provide a seamless rollout of the protocol. This upgrade protocol is part of what's called the WebSocket Opening Handshake.

WebSocket Opening and Closing Handshake

To open a WebSocket connection, a client sends HTTP request to the server, with the header field: Upgrade: websocket. The server responds to this request with a 101 status code and the same header field in return. The 101 status code indicates that the server is switching protocol. Once the client receives this response, the open event in the API above is triggered, as the connection is established. This short exchange of HTTP packets is what's called the

WebSocket opening handshake. Actually this was a simplification since there's also an exchange of keys going on. This key exchange is there to make sure the two parties talk the exact same protocol version.

Similarly to the opening handshake, WebSocket also has an closing handshake. This handshake is there to differentiate between intentionally and unintentionally closings of the connection. As you read in the API description, the user can send a status code and a UTF-8 text string to tell the server why the connection was closed.

HTTP Request:

```
GET /chat HTTP/1.1
Host: server.example.com
Upgrade: websocket
Connection: Upgrade
Sec-WebSocket-Key: x3JJHMbDL1EzLkh9GBhXDw==
Sec-WebSocket-Version: 13
Origin: http://example.com
```

HTTP Response:

```
HTTP/1.1 101 Switching Protocols
Upgrade: websocket
Connection: Upgrade
Sec-WebSocket-Accept: HSmrc0sMlYUkAGmm5OPpG2HaGWk=
```

Figure 9: WebSocket opening handshake example[14]

Message Format

To improve the lives of developers and to keep its simplicity, WebSocket abstracts away some of the roughness of TCP. When you want to send a message over a TCP socket, the message might be divided into several chunks and you have to deal the fact that they are delivered as chunks and not as whole messages when they arrive. WebSocket takes care of this for you and the «message» event is only triggered once an entire message is delivered. Even though the protocol abstracts away the framing for the developer, messages are indeed sent as chunks - or frames. A WebSocket frame looks like this:

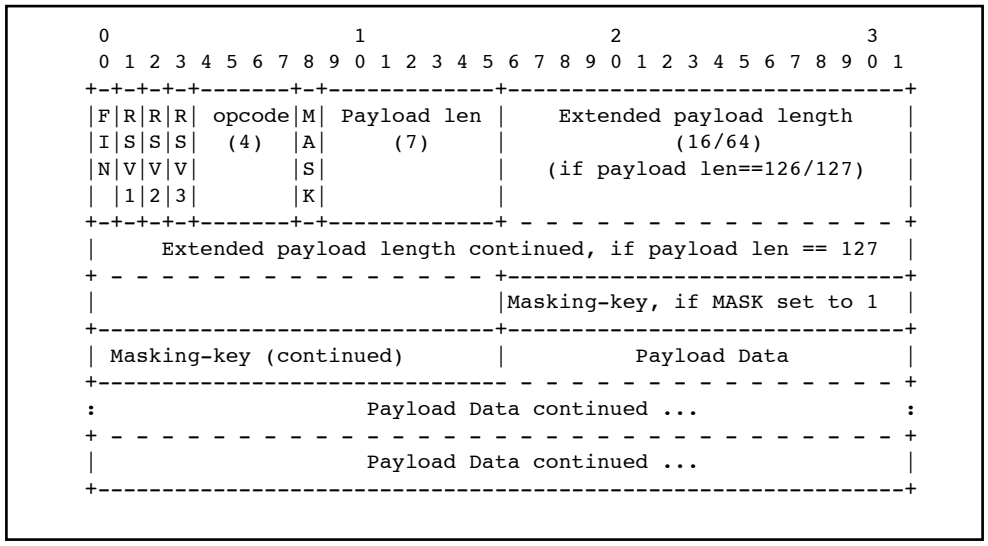


Figure 10: The WebSocket frame as defined in RFC6455[13]

- FIN and RSV bits: The first bit in the frame is the FIN bit. This is set to 0 if there is a following frame to the message being sent. The next three bits are there for protocol extensions. Extensions will be discussed later.

- Opcode: The following four Opcode bits symbol the type of the frame payload. For example if you're sending UTF-8 text this would be 1, while for binary data it would be 2

- Masking: The mask bit indicates whether the payload has been masked or not. All WebSocket messages sent from a client to a server must be masked in order to avoid HTTP proxy issues. If the mask bit is set, a 4 byte masking key is added to the frame header.

- Payload Length: WebSocket frames encode the payload length with a variable number of bits, so that small frames (0-126 bytes) only need 7 bits to encode the length. For payloads between 126 and 216 an extra two bytes (7 + 16 bits) are added and for larger frames an extra 8 bytes (7 + 64 bits) are added.

Subprotocols and Extensions

The simple, yet powerful nature of the WebSocket API makes it perfect to build higher level protocols and frameworks on top. This was thought of when WebSocket was designed and the protocol fully support what is known as *subprotocols*. When creating a WebSocket connection you can pass in an array of subprotocol names like this:

```
var ws = new WebSocket('ws://example.com', ['proto1', 'proto2']);
```

In the above example the client tells the server at example.com upon connection that it speaks both 'proto1' and 'proto2' and if the server knows these, the server can chose which one to use, but only one at a time. There are several official protocols[15], such as Microsoft SOAP and unofficial open protocols such as XMPP. There's of course possible for everyone to create additional WebSocket subprotocols.

Together with subprotocols, there's another way to supplement WebSocket with additional features: WebSocket extensions. Unlike subprotocols you can extend your WebSocket connection with several extensions. An extension is a supplement to the already existing protocol and both browser and server must support it. Extensions can be added with the *Sec-WebSocket-Extension* header and following is an example that compress frames at source and decompress at destination:

```
Sec-WebSocket-Extensions: deflate-frame
```

2.5.3 WebSocket Libraries and Deployment

All modern web browsers support WebSocket, but there are sadly still lot a user running out of date browsers and as a result it can be beneficial to a WebSocket emulation library - a library that uses other techniques if WebSocket support isn't there, while keeping a single interface for the programmer to deal with. There are quite a few of those libraries out there, but the two most notable are Socket.IO[16] and SockJS[17]. Both will first try to use WebSockets and fallback to other real-time techniques if browser support isn't there, while

keeping the same programming interface. Fallback technology includes Long Polling, HTTP Streaming and even Adobe Flash Sockets for Socket.IO. SockJS tries to emulate the WebSocket API as close as possible, while Socket.IO adds more features on top. Socket.IO is targeted at Node.js, which is a JavaScript backend platform, while SockJS can be used with other backends. For traditional Java backends like Java EE, WebSocket is also fully supported, with JSR 356[18]. On the .NET side there's SignalR[19] which works the same way.

One would think that these WebSocket emulation libraries would become redundant once all users run up to date browsers with WebSocket support. But that might not be the case. The fact is that the WebSocket API could be too simple and barebones, resulting in a lot of boilerplate code. SocketIO for example gives the abstraction of rooms that users can join and broadcast abilities[20].

2.5.4 WebSockets vs. HTTP

WebSockets are great, but won't replace HTTP. Instead the two protocols will work together to bring real-time web applications to market. There are features of HTTP, that WebSockets don't provide. It doesn't make sense to download all website assets over WebSocket, as HTTP already has great caching abilities. Cookies is another part of HTTP not available to WebSockets.

WebSocket is an easy to use, modern and powerful TCP like protocol, that in some areas even outshines TCP, with its easy subprotocol scheme and frames being abstracted away. The web has finally caught up with platform native applications in terms of real time networking capabilities. One of the issues with HTTP, was the large amount of header data. With my HTTP GET example to www.uio.no, every request and response had several hundred bytes of meta data. The meta data is there to give a sense of state to an otherwise stateless protocol. Since WebSockets are stateful, message size can be tiny in comparison (but requires more action at the server). With our previous stock price app example each stock price update would not be many bytes sent from the server, probably under 126 bytes, meaning that the total WebSocket frame headers size would be only *3 bytes* (2 for FIN, RSV and Opcode bits, 1 for mask bit and payload length). 3 bytes is a really small overhead compared to what you get with HTTP.

HEAD OF LINE BLOCKING

2.6 Server Sent Events

For some real-time applications there are no need for the client-to-server capability that WebSocket provide. The stock price example earlier is a great example of this. All we need is a way to quickly push data from the server to all connected clients. Server Sent Events is an addition to HTML5 that gives us just that. Just like with WebSocket there are two parts of SSE you need to understand. First it is the programmer API called EventSource. Second is the protocol itself.

2.6.1 EventSource API

The EventSource interface is quite small and developer friendly. And is defined like this by W3C:

```
[Constructor(in DOMString url)]
interface EventSource {
  readonly attribute DOMString URL;

  // ready state
  const unsigned short CONNECTING = 0;
  const unsigned short OPEN = 1;
  const unsigned short CLOSED = 2;
  readonly attribute unsigned short readyState;

  // networking
           attribute Function onopen;
           attribute Function onmessage;
           attribute Function onerror;
  void close();
};
EventSource implements EventTarget;
```

Figure 11: The EventSource API[21].

Right off the bat it looks very similar to the WebSocket API, and it is. There are different ready states available and open, message and error events you can listen for. There's also a method to close the connection. The figure below shows how simple it is to open up a connection and listen for messages:

```
var source = new EventSource('http://example.com/sse');
source.onmessage = function(m) {
     // Code to be executed once a message has arrived
}
```

Figure 12: How to connect to a SSE endpoint and listen for updates.

2.6.2 Event Stream Protocol

Server Sent Events is actually implemented as HTTP Streaming over a long lived HTTP connection, but with a consistent and simple API. Other advantage over regular HTTP Streaming includes automatic reconnects when the connection is dropped and message parsing[22].

Syntactically, what differs SSE from HTTP Streaming is the Accept and Content-Type header fields. The new value is "text/event-stream". To illustrate how this exchange is done and how data is sent, see the following figure.

HTTP Request:

```
GET /stream HTTP/1.1
Host: example.com
Accept: text/event-stream
```

HTTP Response:

```
HTTP/1.1 200 OK
Connection: keep-alive
Content-Type: text/event-stream
Transfer-Encoding: chunked

retry: 15000

data: First message is a simple string.

data: {"message": "JSON payload"}

id: 42
event: bar
data: Multi-line message of
data: type "bar" and id "42"
```

Figure 13: Part of example found in High Performance Browser Networking[22].

In the example above you can see how the server sets the client reconnect interval to 15 seconds. Also server-sent data can be pure text or JSON. Also it's possible to send an id and custom event associated with that message.

2.6.3 Server Sent Events Adoption

So with a simple API and developer friendly features like automatic reconnects, SSE should be the obvious choice for server push on the web? Sadly that is not the case. The way I see this, there are two reasons for it. First and in some cases, not very important - you can only send string data. If you need to send binary it would have to be converted using base64 encoding, but this adds some overhead. Second, adoption is not perfect. Every modern browser except Internet Explorer supports SSE, but since IE accounts for a very large portion of the market, choosing SSE alienates those users.

2.7 Node.js - JavaScript Everywhere

When developing for the web, you need to develop on two distinct ends - the front and backend. Unlike the way it is for OS native applications, the web front end is limited when it comes to development choices. Your code have to be JavaScript, HTML and CSS. This is not entirely true as shown with newer languages like Dart[REF], CoffeeScript[REF] and TypeScript[REF], that acts as replacements for JavaScript. Still, the browser don't understand

these languages, so they ultimately need to be compiled to JavaScript. Same goes for HTML and CSS. JavaScript is in a sense the assembly language for the Web.

On the backend however, you are free to chose your preferred web framework and language. Traditionally Java and .NET with frameworks such as Spring and ASP.NET respectively have been very popular. Even though the clear separation of front- and backend works fine, a newer platform called Node.js shows there was a need for a more unified web development process.

As web applications became more and more complex following Web 2.0, web developers spent increasingly more time writing rich client side applications in JavaScript. The context switch from front end JavaScript to an other server side programming language could be cumbersome. So when the creator of Node.js Ryan Dahl introduced server side JavaScript in 2009, many developers found the promise of JavaScript everywhere promising.

Node.js is a JavaScript runtime environment built upon Google Chrome's V8 JavaScript engine. As V8 is mostly written i C++[23], it can run directly on the hardware and is as a result, really fast.

In addition to JavaScript on the server, Node.js brings some new attributes to server side web development:
- Non blocking code.
- Single threaded development environment.
- The lightweight package manager NPM.

In traditional threaded web servers, a new thread is spawned for each new connected client and the server context switches between all threads and runs their code. However, most of the time, web servers are doing IO, typically querying a database or reading a file. IO operations block the running thread and the server and have to wait for the IO operation to complete. This takes up precious CPU cycles and the server compensates by doing context switches between threads. The problem is that context switches are expensive and threads take up memory, along with the fact that programming for a threaded environment is hard.

Node.js breaks the threaded programming paradigm with something called an Event Loop. The event loop is an ever-going loop that constantly looks for triggered events. Examples on events can be a newly connected client or an answer to a database query. The event loop lets you program in a single threaded environment that takes full advantage of the CPU. Because of the event loop, Node.js has proven to scale quite well.

To show how the two different programming styles are, consider the following examples:

```
var result = database.query("some query"); // Code blocks here
// Result is fetched
something else;
```

Figure 14: Blocking code

```
database.query("some query", function(result) {
      // Result is fetched
});
something else;
```

Figure 15: Non-blocking asynchronous code

In the first example you can see that the first line blocks the following lines until the database query result is stored in the variable *result*. This is how programming is done in a threaded and synchronous environment. Most programming languages like Java follow this model.

The second example shows how you typically write Node.js code. The difference here is that we send in a *callback* function to the query function itself. The callback function is called whenever the database has responded and is triggered by the event loop. The code following the database query can execute immediately.

Programming in an asynchronously manner is fundamentally different to the synchronous style most back end programmers are used to with Java. Front end developers on the other hand, have been programming like this for some time. Ryan Dahl said during his Node.js introduction that JavaScript is the perfect language for a non-blocking environment[24]. The browser already has an event loop constantly listening for events such as button clicks. Node.js unifies web development around only one programming style and language.

2.8 Performance Testing

Because this thesis will be about benchmarking technologies, it's appropriate to introduce some basics of performance testing. It's become increasingly more important to performance test your system. In these days of the internet and the web, many applications launch to uncertain amounts of popularity. Unexpected high demand lead to load levels that can severely slow down or even break applications.

To determine what technology is the most efficient under a set of certain criteria, we can carry out performance tests. As stated in the book Performance Testing Guidance for Web Applications, "Performance testing is a type of testing intended to determine the responsiveness, throughput, reliability, and/or scalability of a system under a given workload"[25]. For a product launch on the internet, it's vital to know whether your systems can withstand the expected workload, especially on launch day. Testing is therefore crucial and should be a integral part of software system development. Performance testing can also help you identify bottlenecks in your system and assist you in building an as efficient solution as possible. Even though the book focused on implementing performance testing into an agile development process for a real world project, it functioned fine as a guide for this thesis. I used to book to learn about what performance testing is, what types of tests can be run and what to look for. Performance testing can be divided into subcategories:

- Load testing: Load testing an application means putting it under a certain amount of demand and measuring it's response time and resource use.

- Stress testing: Stress testing is putting a system under extreme levels of workload and see how far it is possible to push it before it breaks. Stress tests can also help you find the weakest link in your system causing bottlenecks.
- Soak testing: This type of test is usually done to determine memory leaks. To get an accurate leakage picture of a system, this test usually have to be run for a long time.
- Spike testing: Spike tests are conducted to see how a system reacts to sudden spikes of workload.

3 Methodology

3.1 Introduction

So far, two types of real-time web applications have been presented. The first is a server push-type of application - the stock price example illustrates this perfectly. It consists of an inactive client regularly receiving or polling updates from an active server. The second real-time application type is illustrated by the chat app example. In this case the clients, in addition to the server, are also active. Messages are going in both directions. Every client have the ability to send a message.

Because there are two types of real-time applications, the project part of this thesis will consist of two distinct test scenarios, one for server push and one for bidirectional messaging. In both scenarios WebSocket, Server Sent Events and HTTP Long Polling will be used and compared to each other. Each test will run with a given number of connected clients, ranging from 1 to 500 with increments of 50. In addition, each test will be run 10 times with the given number of clients to provide a satisfying average.

In this chapter, the test scenarios, and the choices made in regards to them will be presented. In addition there are some notes on the development. First up, what and how to monitor.

3.2 Monitoring

As stated with the problem statements, the mission of this thesis is to compare WebSocket to other real-time technologies for the web and try to answer what types of applications that would benefit from WebSocket. To get an accurate picture, I have chosen to load and stress test the technologies in question. This is done by gradually increasing the number of connected clients, and at one point the server is so hardly stressed that I will see a sudden drop in server response time.

On the server side, you want to use as little server resources as possible, enabling a high number of clients. The interesting metrics on the server side is then naturally *CPU load* and *memory footprint*.

As a user of a real-time web application, you do not care about how much stress the server is under. For a user, the only thing that matters is that the application works as intended, and for a real-time application that means it has to feel responsive and quick to use. The right measure on the client side is then *response time*.

To summarize what metrics is used in the tests:
- CPU and memory load in the server
- Response time for a client

With what to measure in mind, I had to decide when to measure it. The tests are designed to have three stages:
- The phase before the test - the idle client state
- The phase when the test is running
- The phase when the test is over

3.2.1 The phase before the test - idle client state

The first phase is the state when the clients are connected to the server, but they are inactive - idle. It is interesting to see how the idle clients affect the CPU and memory usage of the server, and if it affects the response time for other clients. A good result would be low CPU utilization and a small memory footprint when the clients are idle.

3.2.2 The phase as the test is running

This is generally the most interesting phase. It is here we actually see how many clients the transport in test can handle before the response time gets unacceptably high. What is meant by unacceptable high response time is defined in the Analysis chapter below. A good result here would be as low CPU utilization and low response time.

3.2.3 The phase after a test is over

When the test phase is over, it is interesting to see how much memory has been consumed by the server during its test.

To summarize, the following figure shows when and what is measured during the tests.

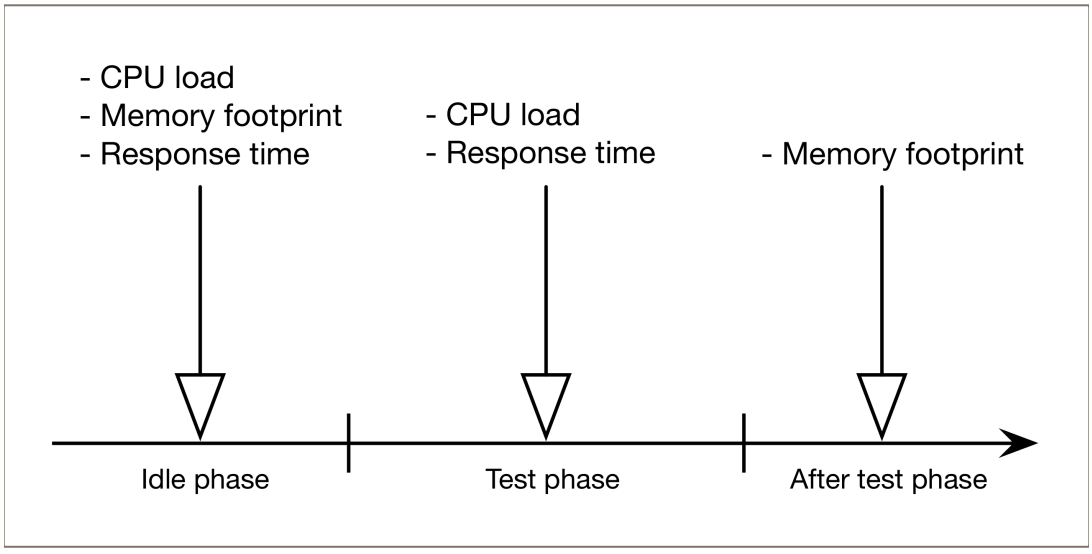


Figure 16: The three test phases and what is measured in each phase.

3.2.4 Over time

How the different technologies perform over longer periods of time can also be interesting. I did however, not want to measure the transports over time, as it relies heavily on the transport's implementation. A small memory leak, for example, can damage the results severely. Also the actual testing would take up a very long time, making it not very suitable for this thesis.

3.3 Scenario 1 - Server Push

3.3.1 Scenario

Note: There is three implementations of this test scenario, one with WebSocket, one with Server Sent Events and one with HTTP Long Polling and the text describing this scenario will not distinguish between the three version. For implementation details, look further down in this chapter.

The first test scenario is a real-time message broadcasting system involving three main components - a backend, a server and a given number of clients. All the clients connect to the server and the server connects to the backend system using a persistent connection. The backend regularly sends messages to the server and it's the server's job to immediately broadcast these to all the connected clients. You can think of this system as the stock price app example from earlier. The clients are then real web browsers connected to a web server that in real time, based on updates from a stock broker, updates the prices of several different stocks.

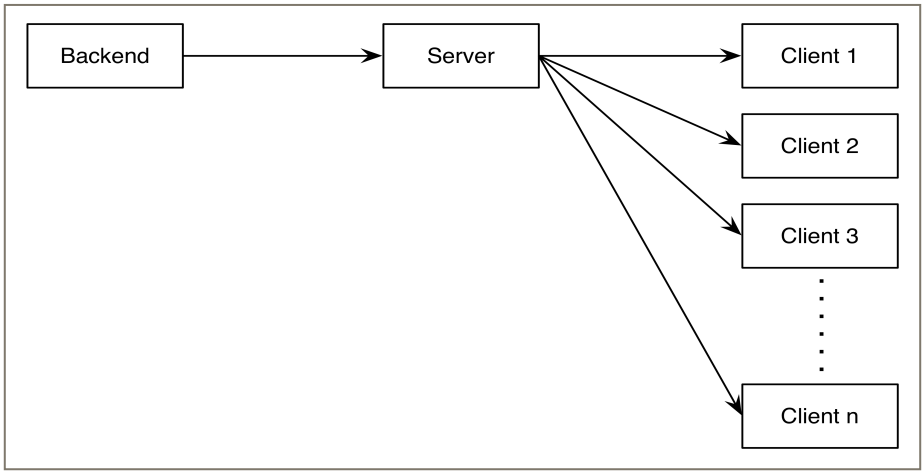


Figure 17: Simple diagram showing the three components. Messages from the backend are broadcasted to all clients.

3.3.2 Detailed Information Flow

Server and Backend

Once the server starts, it immediately connects to the backend. The backend then sends an *info* message to the server, asking how often and how many times a message should be sent. The info message triggers the server to prompt the user for these parameters. Once they are typed in, they are sent to the backend and the backend awaits a *go* message to initiate the message stream. If the user on the server presses the return key, the go message is sent. It's up to the user on the server to make sure all clients are connected before sending the go message to the server.

Once the backend receives the go message it sends a *getReady* message to the server indicating that the broadcast start is imminent. At this point the server forks a monitoring process that right before and during broadcast monitors the CPU usage and memory footprint of the server process.

When the backend has sent all of its messages, it sends a *done* message, signaling the end of the test. This message is also distributed to all clients so that they are aware of the broadcast end.

The monitoring client is also notified that the broadcast is over, and calculates the average CPU and memory usage before and during the broadcast. This is sent to the server that lastly prints it out to the console.

Clients

There's a "master" client process that has two jobs:
- Fork up a given number of client processes that connects to the server.
- Fork up a ping client.

The client processes immediately connects to the server and reports to the master client when they are connected. This way the master client can tell when all clients have obtained connection. A client is dead simple - when it receives a message it just tosses it away and increments a counter to keep track of how many messages it has received. When the done message is received, the client reports to the master client that the broadcast is finished and reports whether it received all messages.

The ping client is a single process that every 50th milliseconds sends a message with a timestamps to the server. The server instantly "pongs" this message back and the ping client calculates the time it took to get a response. When the ping client pings the server after the broadcast is over, the server replies with a done message and the ping client calculates the average response time before and during the broadcast. This is reported to the master client.

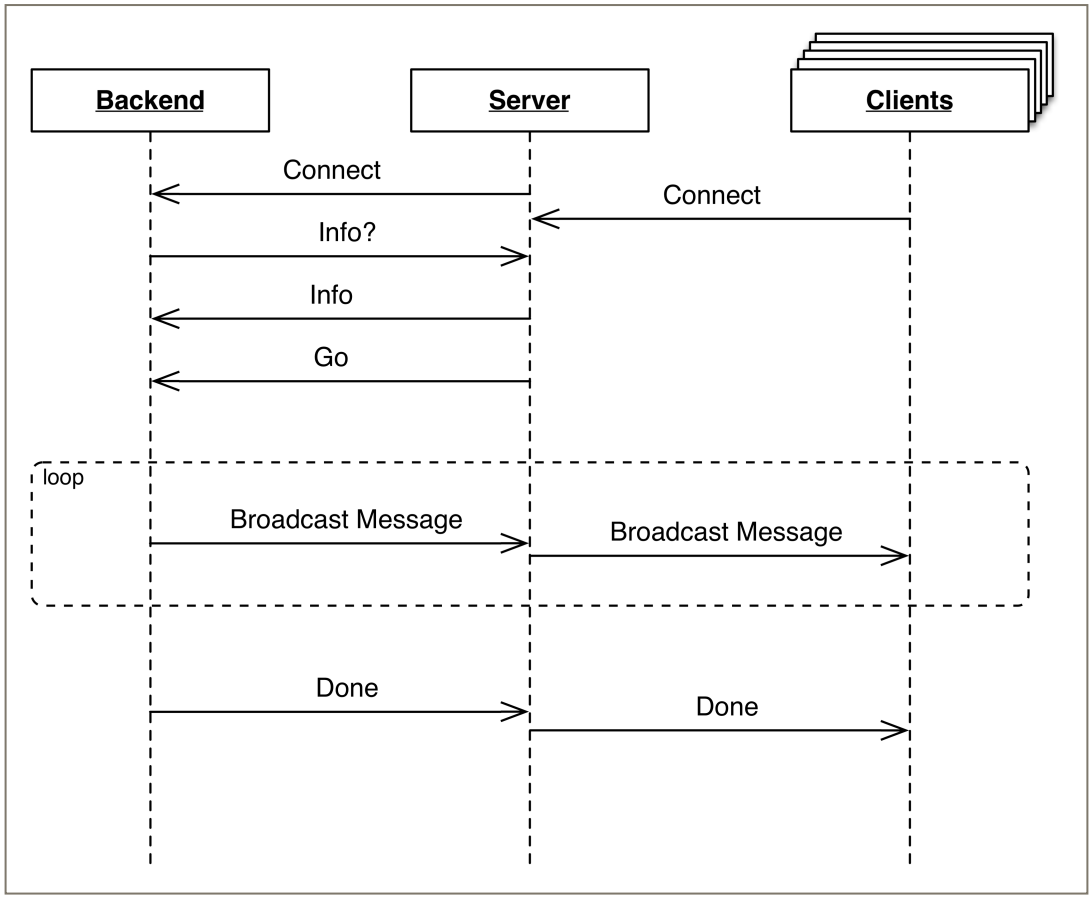


Figure 18: Sequence diagram showing detailed information flow. Note that the master client is not included here.

3.4 Scenario 2 - Bidirectional Messaging

3.4.1 Scenario

Note: There is three implementations of this test scenario, one with WebSocket alone, one with Server Sent Events (HTTP POST for upstream data) and one with HTTP Long Polling (HTTP POST for upstream data) and the text describing this scenario will not distinguish between the three version. For implementation details, look further down in this chapter.

The second test scenario is a real-time chat system. It consists of two main components - a server and a given number of clients. All the clients connect to the server using either WS, SSE or HTTP and after some initial exchange of information, the test is started. During the test, each client regularly sends a chat message to the server. Each and every one of these chat messages are then broadcasted to all connected clients by the server. A simple figure showing the components can be found below.

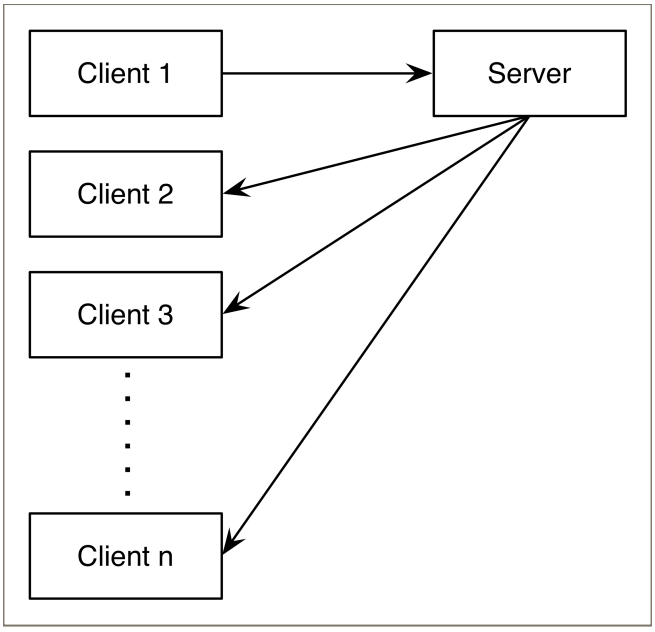


Figure 19: Simple diagram the two components involved in the chat scenario. Client 1 sends a chat message to the server and the server broadcasts this to the other connected clients.

3.4.2 Detailed Information Flow

Clients

As with the first scenario, there is a master client here as well. The master client is started with a parameter from the command line - the number of clients it should spawn. Before the master starts the child process spawning, it exchanges some information with the server. This exchange makes sure that both the server and the master client know how many clients are involved and for how long the test should run.

The master client then spawns the given number of clients. These clients are given the server address and immediately after spawning connects to the server. The client reports to the master client when the server connection is established. Once all clients are connected and ready, the master client sends a *getReady* message to the server. This indicates that the test is about to begin. At the same time, the master client does two things, start a timer that will run out after when the test should end and tell all clients when to start chatting with a *go* message.

The clients then start to send *chat* messages to the server with three second intervals. Details regarding the chosen test parameters are discussed under 3.8 Parameters. Each chat message is timestamped when sent, so that the clients can calculate response time themselves when they receive a chat message.

Once the timeout runs out, the test must be stopped. This is done by telling all clients that the time is up and to send a *timeup* message to the server. The clients then wait for a *done* message from the server. This message includes the number of messages have been sent and the client makes sure that all messages have been received. The client then calculates response times and reports status to the master client before shutting down.

Once all clients have shut down, the master client tells the server with a *finished* message that it is safe to shut down.

Server

The server is started with one parameter - the number of seconds the test should run. When the master client then connects to the server, some information is quickly exchanged, so that both parties know how long the tests should run and how many clients are involved. The server then waits for a *getReady* message indicating that the test is about start. When the getReady message is received, the server must startup the monitor so that it is ready to start monitoring server resources when the chat test is starting.

When the first *chat* message has been delivered to the server, the server tells the monitor to start monitoring server resources. For every chat message that arrives, the server immediately broadcasts it to all the connected or polling clients.

When the chat phase is finished, the server receives *timeup* messages from the clients, meaning that the chat is finished. The server then tells the monitor to stop monitoring. Lastly, the server waits for the master client to send a *finished* message. The finished message indicates that it is safe to shut down the server.

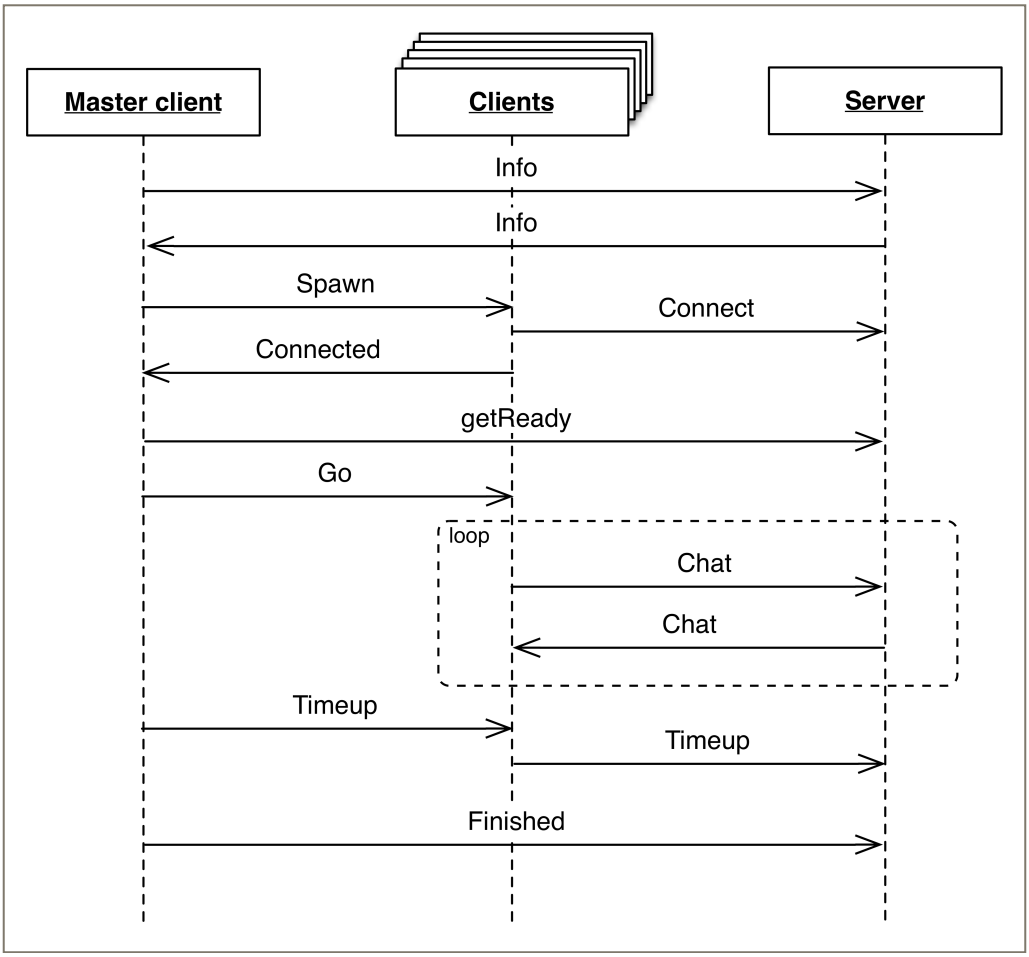


Figure 20: Sequence diagram showing the major flows of information for the chat test.

3.5 Testing environment

3.5.1 Hardware

When stressing the server, it is important that the server is isolated from all the other components. The server process must not be disturbed by some other part of the system. There are several ways to to isolate the server:

1. Isolated process running on same hardware as clients and backend.
2. Isolated virtual machine running on same hardware as clients and backend.
3. Isolated online server instances from an online cloud provider.
4. Isolated on a different physical machine running in an isolated local network.

The first alternative is ideal for development as everything is run on a single computer. For testing however, it is not ideal. It's difficult to tell how the OS context switches between processes and how much time it actually uses on the server. It would be better if the server software was the only process, except for the OS, running. Also since this is about testing network protocols, it's not a good idea to run the clients and server on the same machine. To get an as accurate picture of the server load as possible, the server should be isolated on a hardware level. As a result option three and four remains. The two options both sounds good, but I eventually landed on number four. Most online server instances share physical hardware with other instances and it's hard to tell how the system resources are shared between them. Number four is the setup that gives me the most control over the hardware the server runs on. In addition I had the all the hardware that was needed available at home.

It is important that the machine the server ran on is considerably slower than the one with the clients and the backend, since the server must reach its resource limit before the client machine. Since a resource monitoring process also had to run on the server, two CPU cores or more was preferable. This way the server process could run independently on one core (Node.js is single threaded - see section below) and still be monitored without any performance hit. Of course this all depends on how the OS does process control, but that was the basic idea.

The server ran on the following setup:

Apple MacBook Air 2013
Dual Core Intel Core i5 1.3 GHz
8 GB DDR3
OS X 10.10.1

The backend and clients ran on this machine:

Apple MacBook Pro 2013
Quad Core Intel Core i7 2.0 GHz
16 GB DDR3
OS X 10.10.1

As I didn't want the network to be unreliable or a bottleneck, I decided to have them both running on a cabled 1 Gb/s network.

3.5.2 Programming environment

Node.js was not presented in the background part for no reason, it is the chosen development platform for the practical part of this thesis. The reasoning behind this choice:

Node.js is lightweight, fast and scales well

For this thesis I wanted to benchmark protocols against each other, not web frameworks. Node.js provides very little overhead and since it scales great, the scaling part of this thesis will not be hampered by blocking server code.

Node.js is single threaded

The fact that Node.js only uses one OS process, makes it perfect for monitoring. One process for the server itself and one for the monitoring process can run in real parallel, as long as the CPU has more than one processing core, which is the case with the computers used in this thesis.

Node.js is a platform with cutting edge innovation

When looking at GitHub's most trending and popular repositories[REF], Node.js is the web framework that by far has the most packages and traction. One reason for this is its user friendly package manager NPM[REF].

I only write code in JavaScript

Node.js was a breath of fresh air in the web development world when it arrived. It is not necessarily because JavaScript the language on the server is such a great idea, but because developers can focus on a single programming language for their entire web application, backend to frontend. I consider it a great thing to only have to write JavaScript for this thesis:

- JavaScript is a very expressive and dynamic programming language, meaning I can write powerful applications in few lines of code.
- It increases the readability in this thesis, since there only is one programming language in the examples.
- JavaScript is everywhere. Whatever project you are working on, there is a very high probability that project includes some web components. With the latest edition of OS X by Apple, there's even a JavaScript interface to the OS[REF]. Also, I chose it so that I can learn its quirks[26], as I'm likely to work on some web project in the future.

Node.js is perfect for creating command line programs

Node.js has great support for creating command line utilities [REF]. This makes it perfect for the clients.

3.5.3 Command Line Clients

Kristian Johannessen[REF] had several challenges with his tests and suggested using lightweight console apps or headless browsers instead of full blown web browsers for future work. As the purpose of the tests in this thesis is to compare transport technologies at scale, it is preferable not to use full blown web browsers as clients. Real web browser clients would consume quite a lot of system resources. Self-written console apps on the other hand gives full control and let me put my focus on what I want - the transports.

3.6 Parameters

With the tests being load and stress tests, they had to be run in such a way that it was possible to reach a server resource limit and a break point in response time with the chosen hardware. In this section, I will present and discuss the parameters for both test scenarios.

3.6.1 Maximum Number of Clients

Before tweaking the test parameters, it was important to know what the maximum number of clients the client machine could handle. After some testing, it was clear that 500 had to be the maximum number of clients for the tests. As a default, OS X allows 709 user processes and on the client machine, about 220 user processes was constantly running. To then spawn 500 client processes was not allowed without increasing the OS level maximum process limit. I increased the limit to 1024 with the following commands:

```
$ launchctl limit maxproc 1024
$ ulimit -u 1024
```

Now, 500 additional user processes was not an issue. I could possibly have had more clients, possibly 600, but then OS X would sometimes freeze and tell me that I have too many processes, event though I was way below the limit I manually set. The only solution was a hard reset of the computer. Because of that, I decided to have the maximum number of clients to be 500.

3.6.2 Server-to-Client Scenario

For the first test scenario, there were three different parameters I had to tweak. The fact that the maximum number of clients was set to 500, meant I had to tweak the three additional parameters so that the tests would become stress tests at some point before all 500 clients were used. Furthermore, this had to be true for all three transports I was going to test.

How Long the Backend Should Wait In Between Messages

To make this stress tests, I had to reach a break point in response time and full load on the CPU. Given that I could only have a maximum of 500 clients, clients had to quite rapidly send new messages, in order to stress the server. Every *5th* milliseconds a new message is sent from each client.

The Size of Each Message

This is the last constant. It should resemble a real world message size, so I've decided to set this to the size of a Twitter message - a tweet. The maximum length of a tweet is 140 characters. UTF-8 characters are encoded at different sizes, ranging from 1 byte for standard english characters to 4 bytes for Kanji[27]. The minimum byte size of a 140 character tweet is then 140 bytes, while the maximum tweet size is 560 bytes. I decided to use a 140 english character long tweet. Including 33 bytes of header data, each message is then of size 173 bytes.

The Number of Messages the Backend Should Send

This number is not particularly important as long as it's high enough for the tests to run long enough that the monitoring process will get an accurate picture. Consequently it is a constant set to 5000. Ideally one test now runs for 25 seconds, although they are expected to run longer when the servers are stressed hard.

3.6.3 Bidirectional Messaging Scenario

Just as with the first scenario, the 500 client limit worked as a guide for me to find the right parameter choices here. I wanted to reach the break point in response time for all three transports some time before the 500 client limit.

The Size of Each Message

The payload of each chat message is "Hello! How are you doing today?". That is a very short message, but it resembles a real world chat message. In addition to the payload there are header data, including a timestamp field, a from field and a type field. In total 40 bytes of header data and 31 bytes of payload equals a total message size of 71 bytes.

How Long Each Test Should Run

The first test was designed to run for about 25 seconds. That made it run long enough for an accurate picture, but at the same time not too long, making it too time consuming. I landed on 30 seconds for each test.

Message Spread and Frequency

Each client sends a chat message to the server every three seconds. To have an equal spread of messages, providing an even load on the server, the clients do not start sending chat messages at the same time. They are spread over the three seconds. The following figure shows an example with five clients sending their first to messages.

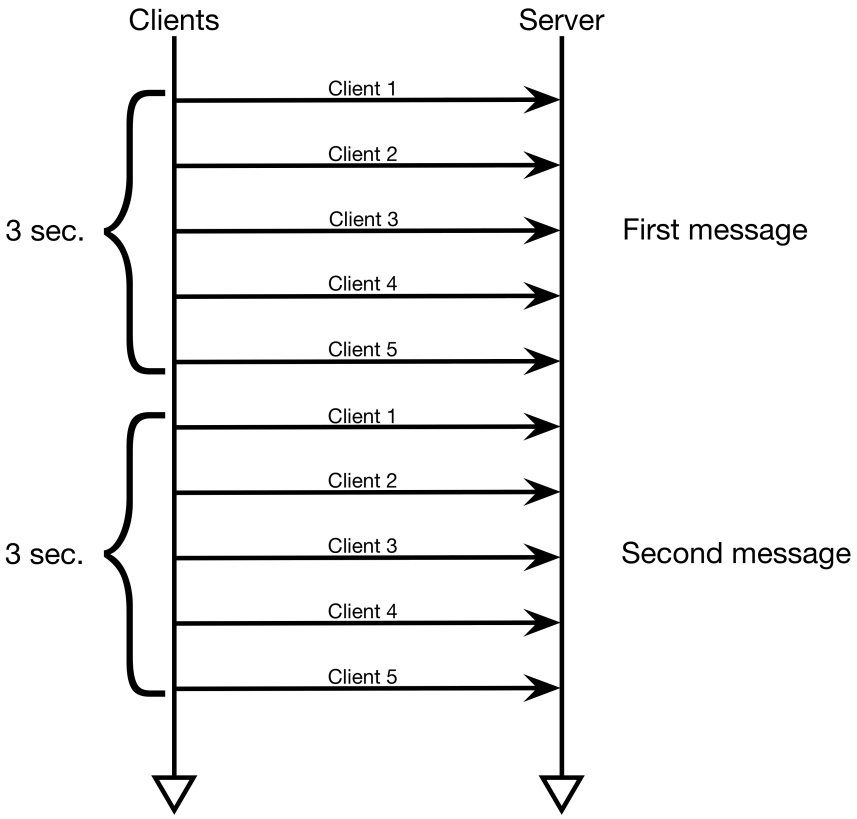


Figure 21: Example showing five clients sending their first two messages.

3.7 Development

3.7.1 Regarding Libraries

The point of this thesis was to test and benchmark different transports - protocols. Benchmarking protocols doesn't really make sense as there are several implementations of different protocols. Testing certain implementations are, on the other hand, of course possible. It was clear from the start that I did not want the thesis to be about comparing different libraries or frameworks, Kristian Johannessen[REF] already did that.

As Node.js is just a simple JavaScript runtime and not a full-blown Web Framework, I had to rely on some libraries. The libraries had to be as small and bare-bones as possible to lay the focus on the transports. By choosing to do all tests on a single platform using small, fast libraries, and lightweight console clients, the focus could stay on the technologies in question.

WebSocket

There are no official client or server implementation of WebSocket for Node.js, so a library had to be utilized. I could have implemented it on my own, but that would have been a thesis on its own[REF]. Thankfully Node.js has a large and dedicated community, so finding WebSocket libraries was easy. Socket.IO is already mentioned, but it offers way more than plain WebSockets, so that would mean a test of a library rather than a protocol. The project

ws by Einar Otto Stangvik[REF] is a server and client implementation of the WebSocket protocol for Node.js. It aims to be as close to the WebSocket API as possible. ws is also one of the fastest[REF] WebSocket implementations for Node.js, making it perfect for testing. In fact, since ws is small and fast, it serves as the low level WebSocket implementation for Socket.IO.

Server Sent Events

There are no native implementation of SSE for Node.js, either as a server or as a client. On the client side the choice fell on *EventSource* by Aslak Hellesøy[REF]. The library is small and doesn't add anything on top of the protocol itself.

I chose to develop the server component myself, as it is just a simple extension to a normal HTTP response. Details on the implementation are below.

HTTP

There was a need for several routes into the server, and the popular web framework *Express*[REF] helped to make that a simple reality. In addition, the small library *request*[REF] made it easy to quickly send HTTP POST or GET requests.

Resource monitoring

To monitor resource usage on the server, the Node.js package Process Monitor[REF] was used. It provides a simple interface to get CPU and memory usage of a process, using the UNIX application ps.

3.7.2 Versions

To see what version of Node, or any of the libraries and frameworks used in this thesis, see the appendix under Software Versions.

3.7.3 Notes on Development - Scenario 1

Backend

The backend system is essentially a WebSocket server using the same library, ws, as the server component. Whenever a client (broadcast server in the test sense) connects, the backend requests broadcast information and awaits a go signal. When all messages have been sent, the backend sends a final done message indicating that the test is over. The backend doesn't close the connection to the server, that responsibility is left to the server itself.

WebSocket Clients and Server

As WebSocket is a persistent connection protocol, each message received from the backend is immediately distributed to connected clients and never stored locally.

The WebSocket clients are started by the program startwsclients.js and given the server address and port over Node.js' interprocess communication method process.send[REF]. The clients discard each broadcast message as they arrive and just keeps track of how many it has received. The server closes the connection and the client report to it's mother process if all messages have arrived.

Server Sent Events Clients and Server

As with WebSocket, each Server Sent Events client has a persistent connection to the server during the broadcast phase. This way each backend message can be discarded after broadcast. As mentioned earlier, the server implementation of Server Sent Events is self-written.

To conform to the Server Sent Events specification, the HTTP header timeout is set to infinity and Content-Type to text/event-stream. This is essentially all needed for a HTTP server to become Server Sent Events-ready.

The clients are started by the program startsseclients.js, uses the EventSource library and works the same way as the WebSocket clients.

```
httpServer.get('/sse', function(req, res) {
      var obj = new SSEClient(req, res);
      clients.connections.push(obj);
      req.socket.setTimeout(Infinity);

      res.writeHead(200, {
            'Content-Type': 'text/event-stream',
            'Cache-Control': 'no-cache',
            'Connection': 'keep-alive'
      });
      res.write('\n');
});
```

Figure 22: From sseserver.js - the Server Sent Events Endpoint

HTTP Long Polling Clients and Server

Consider the example in Figure 6 in the background part. This shows the server need to store each message it receives from the backend. In addition, when requesting new messages, each client must tell the server how many messages it has received, so that the server knows what message or messages to send back, essentially sequence numbers. This introduces a level of complexity not seen in the WebSocket and SSE servers. It can be expected that server CPU usage here is quite a lot higher than for the other servers.

The clients started by starthttpclients.js are also similar to the WebSocket and SSE ones, except that they naturally need to send a new request after each received message.

Resource Monitoring

At first, the CPU and memory monitoring was included into the server process itself, but as the CPU load increased, it started giving irregular and incorrect results. After investigation I learned it was because of Node.js' Event Loop. The monitoring events got lower priority than the broadcast events and eventually never got run as the server always got new broadcast messages to distribute. Consequently it was separated into its own process, forked by the server process.

Ping Client

The ping client is forked by the client starter process and constantly (every 50th millisecond) sends a message to the server with a timestamp. The server immediately responds with the same message. The ping client calculates the response time when the pong is received. For the WebSocket tests the ping client uses WebSocket. For both SSE and HTTP Long Polling, its using standard HTTP.

3.7.4 Notes on Development - Scenario 2

In contrast to the first, the second scenario has messages going server-to-client and client-to-server. Ideally this is developed using a full-duplex stateful protocol that allows for messages going in both directions all the time. However, as previously stated, HTTP is not full-duplex and Server Sent Events is, as the name states, only for messages going server-to-client. To allow the clients to send chat messages to the server, traditional HTTP POST messages was used.

The Client Spread and Message Frequency

As touched upon in the Parameters section above, it was important to have an equal and even load on the server throughout the test. A client is programmed to send a chat message to the server every three seconds and each client is given an id number starting from 1. The process should start sending after (id * (time between each message / client count)). So client number 100 in a test with 400 clients, should start sending after (100 * (3000/400)) = 750 milliseconds.

WebSocket Clients and Server

WebSocket is an ideal protocol for this scenario as it is a full-duplex and stateful. The figure below shows that both incoming and and outgoing messages goes straight to and from the WebSocket component in the server.

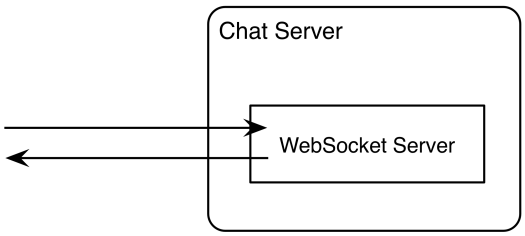


Figure 23: The WebSocket chat server

The server is quite straightforward. When a chat message is received, the server immediately broadcasts this to all the connected clients before discarding that message. The server is also responsible to fork up a monitor process that monitors the CPU and memory usage throughout the test.

The clients are spawned by a mother process called startwsclients.js. It is the mother process' responsibility to make sure the child processes spread the outgoing messages between themselves and don't send them all at once.

Server Sent Events

Unlike WebSocket, a Server Sent Events server has no way to receive messages directly. An additional POST route was therefore utilized. When a client sends a POST message to the server with type "chat", the server immediately broadcasts this message to all clients connected over Server Sent Events. This proved to be a quite simple scheme, even though it was a bit more complex compared to WebSocket.

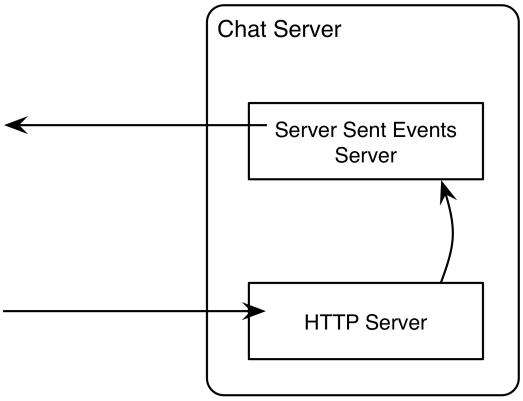


Figure 24: The Server Sent Events chat server with HTTP POST for incoming messages

Just as with the WebSocket variant, there is also here a concept of a mother process spawning all the clients. It is also the server's responsibility to spawn a monitoring process.

HTTP Long Polling

Just as with Server Sent Events, HTTP POST had to be used for the upstream of chat messages coming from the clients. However, unlike Server Sent Events and WebSocket, there is no concept of "connected clients" as they "lose" their connection when the polling is answered. See Figure 6 from the background part for an example, showing that there is a need to store every incoming chat message on the server side. This leads to a significant increase in complexity. Each client's polling request includes an integer that is the index of the next message to receive. This is done similar to the system used for scenario 1. The figure below shows the complexity of the implementation.

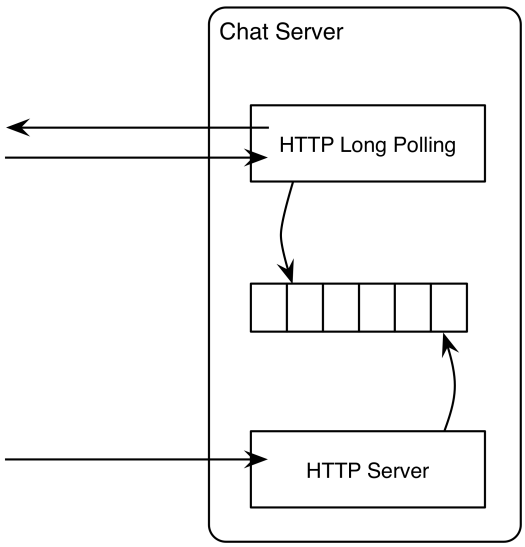


Figure 25: The HTTP Long Polling chat server with local array as message store and HTTP POST for incoming messages

Just as with the WebSocket and Server Sent Events variants, there is also here a concept of a mother process spawning all the clients. It is also the server's responsibility to spawn a monitoring process.

3.8 Limitations

There are a few limitations to the research described in this chapter. First, there is the quality and correctiveness of the test implementations. There is always a chance that the JavaScript code is not written in a optimal and satisfactory way. It could even be worse, that the implementation is outright wrong. But this uncertainty will always be there, as long as humans write the code. Even with bigger projects and frameworks that are tested by thousands, bugs and errors can occur[28].

A second limitation is the fact that I have chose to use just one software platform for my tests. This choice was influenced by a recommendation from Kristian Johannessen[29], but can be a limiting factor. Consider the scenario where the three tested transports' performance with Node.js is far off the average of all software platforms. In that case, the results in the next chapter would be an outlier and not indicate the real transport performance.

GC

3.9 How to Run the Tests

Node.js is required to run the tests. It might also be required to increase the OS limit for user processes.

3.9.1 Scenario 1

It is required to start the backend before the server. Once started, the backend listens on port 9000. The servers always listen on port 8000.

First, start the backend like this:
```
$ node backend.js
```

Then start the desired server like so:
```
$ node <ws/sse/http>server.js <backend ip> <backend port>
```
Example:
```
$ node wsserver.js localhost 9000
```

Lastly, start the clients:
```
$ node start<ws/sse/http>clients.js <server ip> <server port> <client number>
```
Example:
```
$ node startwsclients.js localhost 8000 128
```

3.9.2 Scenario 2

First start the server like this:
```
$ node <ws/sse/http>server.js <backend ip> <seconds the test should run>
```
Example:
```
$ node wsserver.js localhost 30
```

Then start up the clients like so:
```
$ node start<ws/sse/http>clients.js <server ip> <client number>
```
Example:
```
$ node startwsclients.js localhost 128
```

4 Results

4.1 Introduction

In this chapter, the results from the tests will be presented. There is no discussion of the results in this chapter, but simply a presentation of the numbers as they are found. The discussion and analysis is found in chapter 5. For full versions of the test results, including numbers from all test runs, see the Appendix.

The results and the chapter is structured in this way:

1. The idle client state, where the clients are connected or polling, but inactive.
2. The test phase for both test scenarios
3. Memory footprint after the tests

4.2 Idle Client Phase

As discussed in the previous chapter, the first test phase is the phase when all clients are connected/polling, but inactive - idle. It is desirable that idle clients consume as little server resources as possible and do not impact the response time for other clients. The idle client phase is independent of the test scenario.

4.2.1 CPU Load

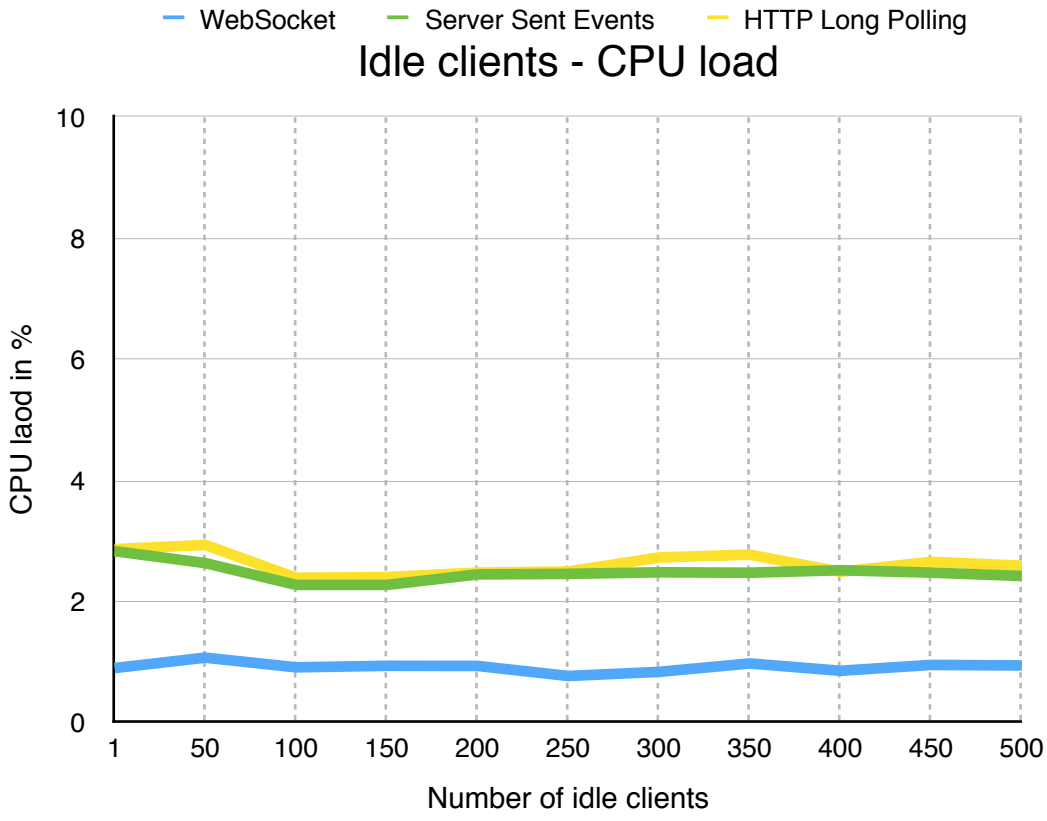


Figure 26: The CPU load for all three transports during the idle phase.

When all the clients are connected and idle, we can see that HTTP Long Polling and Server Sent Events performs very similarly, with fairly low and consistent CPU load between 2% and 4%. The increased number of connected clients doesn't seem to affect the CPU load in any way, as long as the clients stay idle. WebSocket is also very consistent in this regard, but performs even better. With WebSocket we see the CPU load hover around 1%.

4.2.2 Memory Footprint

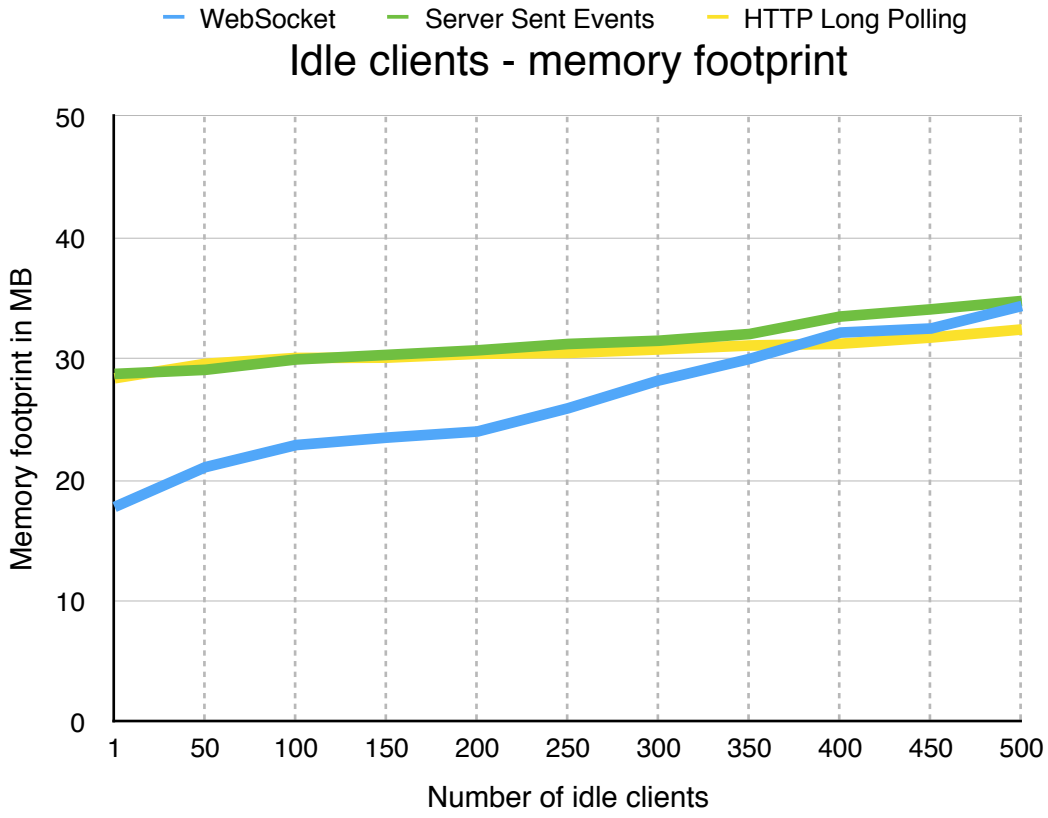


Figure 27: The memory footprint for all three transports during the idle phase

The results show that both Server Sent Events and HTTP Long Polling servers, only see a small gradual increase in memory usage as the user count rises. The WebSocket server, on the other hand, sees a higher increase, but initially the footprint is significantly lower.

4.2.3 Response Time

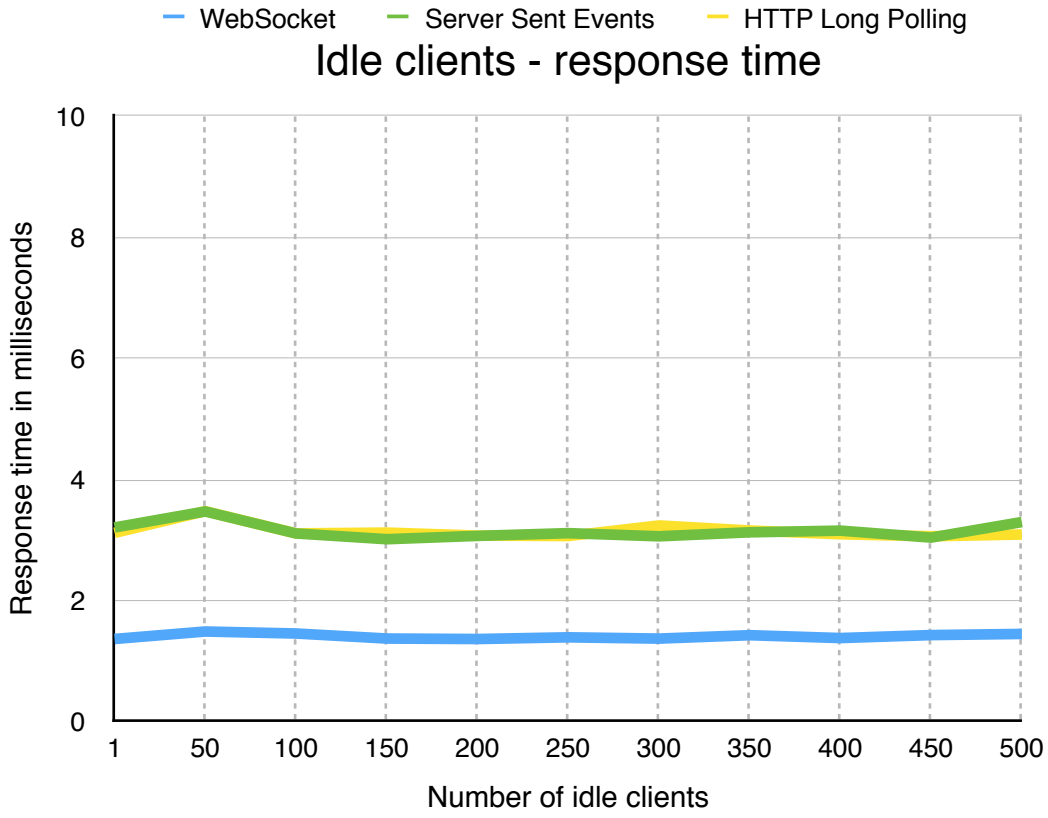


Figure 28: The response times for all three transports during the idle phase

Similarly as with the CPU load, the increase in connected clients, does not seem to impact the response time. And also identical to the CPU load metric, WebSocket performs better compared to HTTP Long Polling and Server Sent Events, which in addition are really close.

4.3 Test Phase - Scenario 1

4.3.1 CPU Load During Broadcast

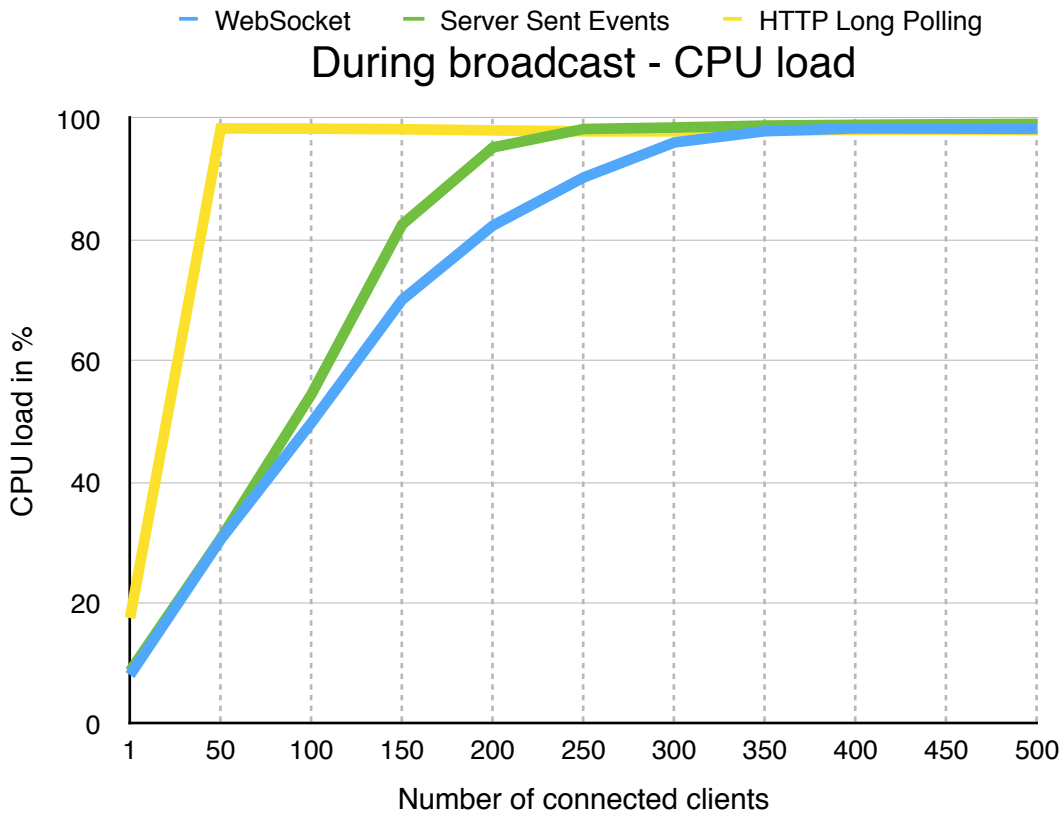


Figure 29: The CPU load during the first test scenario's test phase

The most notable aspect here is that the HTTP Long Polling server reaches its CPU load peak very early on. With only 50 clients polling we already see over 98% CPU load. Other than that we can see the Server Sent Events and WebSocket servers start off similarly before the WS server slowly pulls off to be the most efficient one CPU usage vise. The SSE server reaches 98% at 250 clients while the WS server reaches 97,95% at 350 connected clients.

4.3.2 Response Time During Broadcast

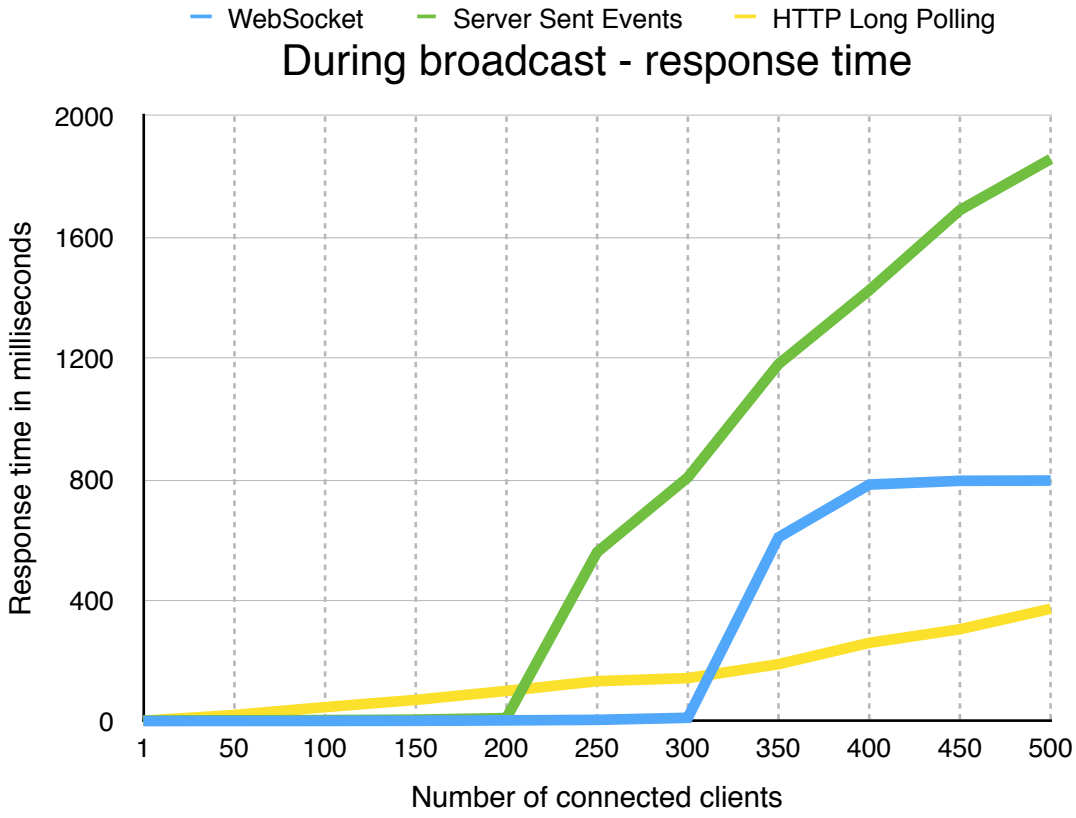


Figure 30: The response times during the first test scenario's test phase

Considering how much CPU load the HTTP Long Polling server used from the start, one could expect it to be outperformed by the other servers all the way from the start. That is also the case, but only initially. When the WebSocket and Server Sent Events servers reaches maximum CPU load at around 98% load, they really struggle to keep the response time low. With Server Sent Events it skyrockets all the way up to over 1,8 seconds, while WebSocket stays below 1 seconds at around 800 milliseconds.

4.4 Test Phase - Scenario 2

When the second test scenario was finished developed, and some initial tests were run, it was clear that the response time varied a bit more than in the first test scenario. This made me calculate the the median in addition to the average response time. After all the tests were run though, it was clear that the median was not too far off from the average, so in this chapter I will only present the average response time. The median results can be found in the appendix.

4.4.1 CPU Load During Chat

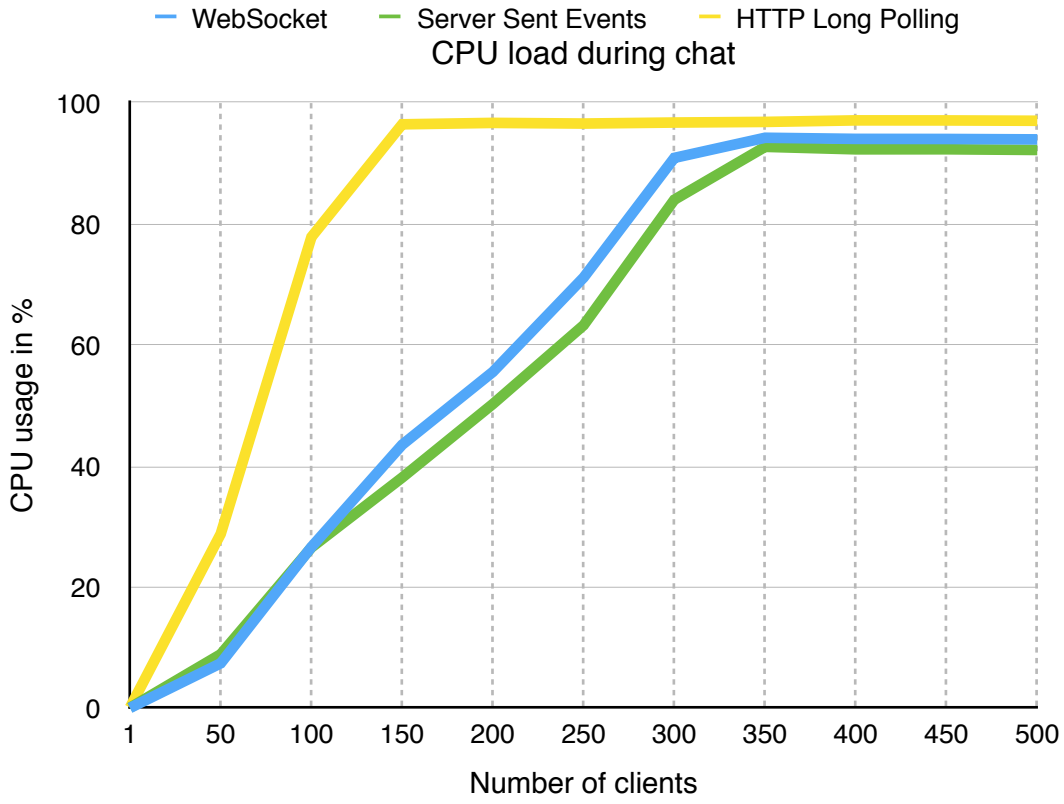


Figure 31: The CPU load during the seconds test scenario's test phase

Not too different from the first scenario, we here as well see that the HTTP Long Polling server immediately requires a lot more CPU power than the other servers. The HTTP Long Polling server reaches its maximum CPU utilization around the 150 client mark, while both the WebSocket and the Server Sent Events servers go up to 350 clients before plateauing out at a maximum. It is interesting to see that for this test scenario, the maximum CPU utilization for the Server Sent Events and WebSocket servers is a bit lower than the HTTP Long Polling counterpart.

4.4.2 Response Time During Chat

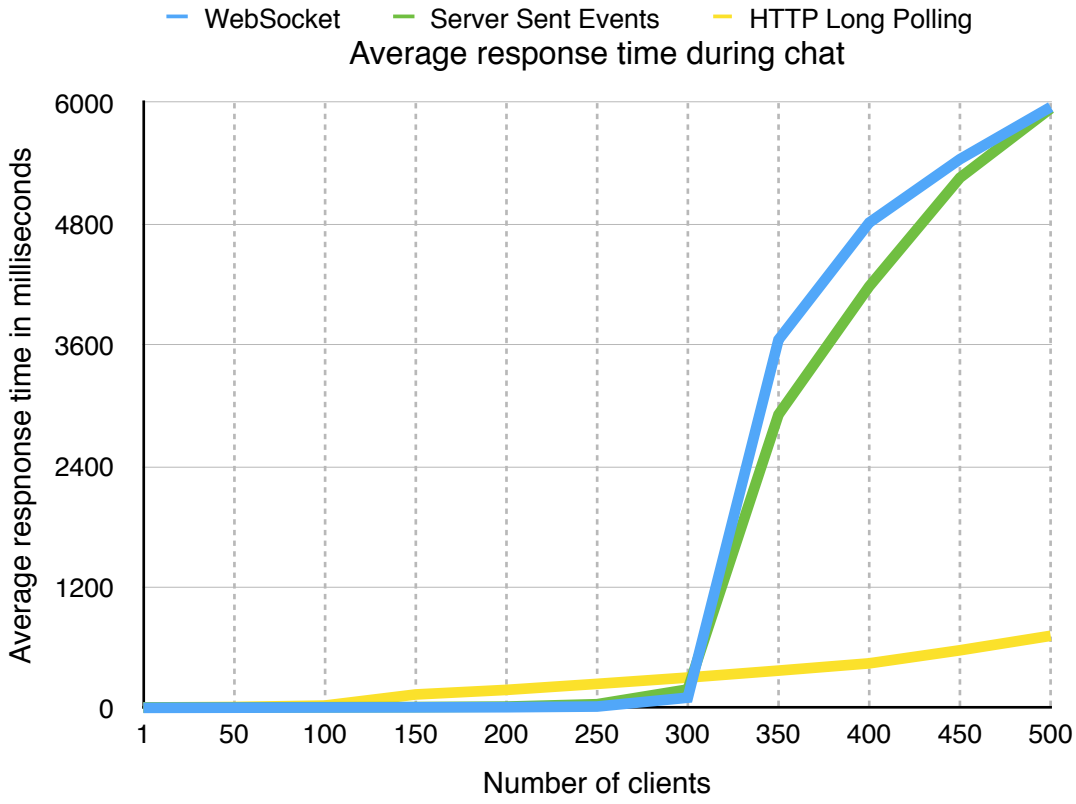


Figure 32: The response times during the second test scenario's test phase

Very similar to the first scenario we see that the WebSocket and Server Sent Events servers perform excellent up until the point where they reach maximum CPU utilization, at around 350 connected clients. The HTTP Long Polling server slowly but steadily increases its response time as the client count increases, seemingly independent of the actual CPU load.

4.5 Memory Footprint After Tests

4.5.1 Test Scenario 1

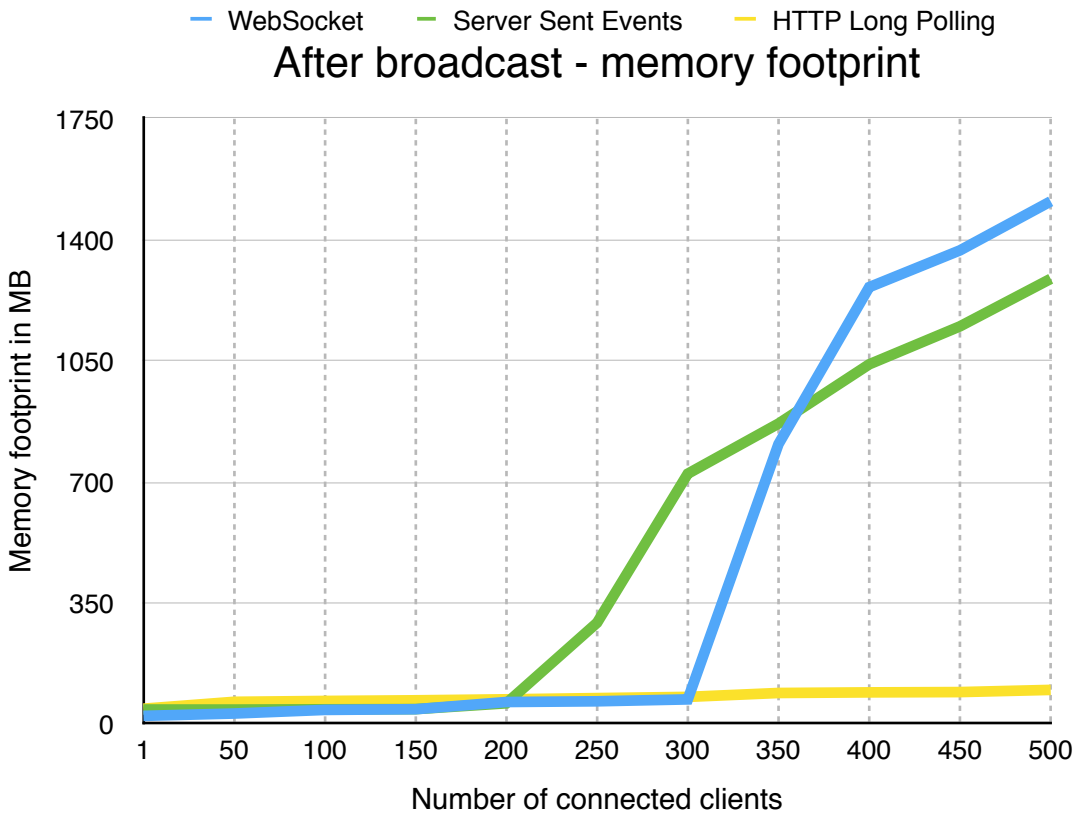


Figure 33: The memory footprint right after the first test scenario's test phase

Just as with the response time, we see a hefty jump in memory footprint when the WebSocket and Server Sent Events servers reaches their maximum CPU utilization. Again, the HTTP Long Polling server performs more predictable with its steady increase independent of the CPU use.

4.5.2 Test Scenario 2

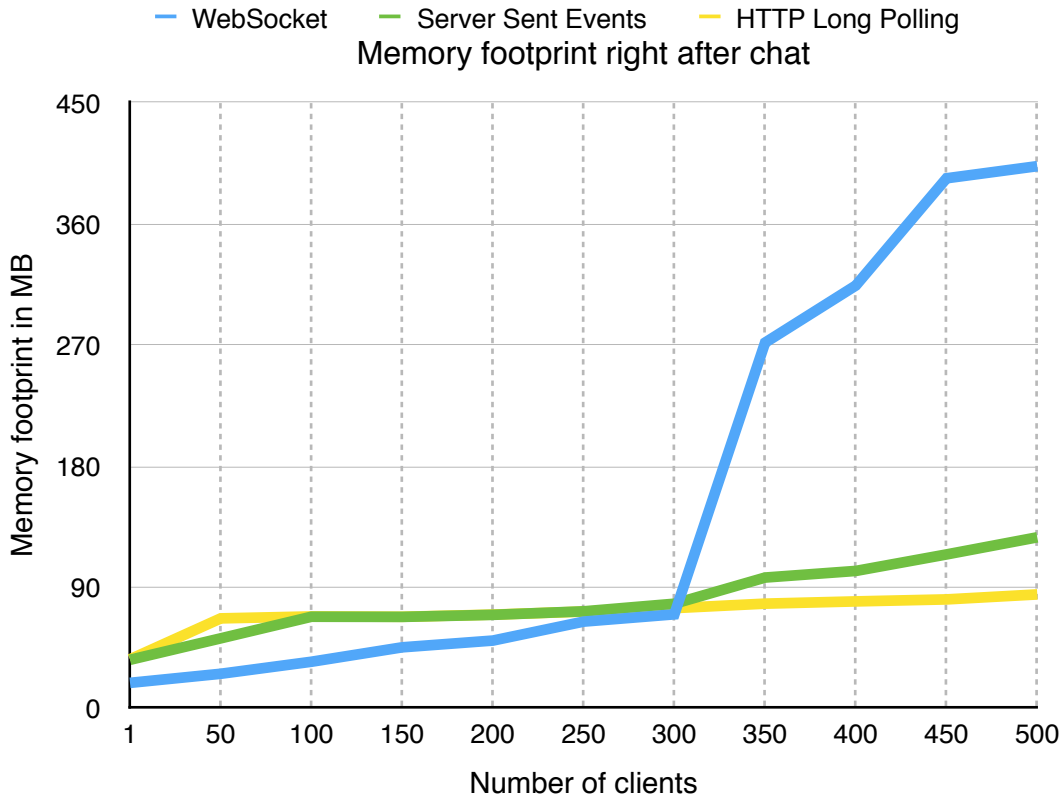


Figure 33: The memory footprint right after the second test scenario's test phase

Unlike the first scenario, this time around it is only the WebSocket server that has an sudden increase in memory footprint. The Server Sent Events server joins the HTTP Long Polling server in being predictable with its steady increasing memory footprint curve.

5 Discussion

5.1 Introduction

This chapter includes detailed discussion and analysis of the results from the previous chapter. The three different transports, will be discussed in three different sections:

1. The idle client state, where the clients are connected or polling, but inactive.
2. The load testing part, where the server is not under maximum stress levels.
3. The stress testing part, where the server is under great levels of stress with maximum CPU load.

The most interesting results come from the stress testing, where we see some anomalies with regards to excessive memory usage and sudden spikes in response times. These unexpected results needs explanation, and I will try to clarify them with possible solutions.

Lastly to not see how the three different transports compare in terms of performance, I will look more into how usable they are, from a programmers perspective.

Lastly some notes regarding the different development styles and programmer friendliness will be discussed.

Before diving into the results, there needs to be a set of response time limits that form a base for how long an unacceptable response time is. For this, I have chosen to use Jakob Nielsen's 3 Important Limits.

5.2 Response Times: The 3 Important Limits

This heading is the name title of a article[30] written by Jakob Nielsen and is an excerpt of his 1993 book Usability Engineering. In this article Nielsen presents three response time limits for all types of applications, including web applications. The article says:

> "**0.1 second** is about the limit for having the user feel that the system is **reacting instantaneously**, meaning that no special feedback is necessary except to display the result.
> **1.0 second** is about the limit for the **user's flow of thought** to stay uninterrupted, even though the user will notice the delay. Normally, no special feedback is necessary during delays of more than 0.1 but less than 1.0 seconds, but the user does lose the feeling of operating directly on the data.
> **10 seconds** is about the limit for **keeping the user's attention** focused on the dialogue. For longer delays, users will want to perform other tasks while waiting for the computer to finish, so they should be given feedback indicating when the computer expects to be done. Feedback during the delay is especially important if the response time is likely to be highly variable, since users will then know what to expect."

The 10 second limit can be discarded, as none of my test runs exceeded it. The remaining two limits form a great base for what is acceptable results in a real-time setting. Of course it varies from application to application which one of these limits is kept. For a chat application it is probably not too important that a message arrives within 0.1 seconds, but it would be nice not having to wait 10 seconds. 1.0 seconds for a chat application seems reasonable. There are other types of applications where the 0.1 second limit seems a better fit. Lets say you power a radio controlled vehicle, maybe a quadcopter. When controlling that vehicle, 1.0 second would seem like an eternity.

5.2 Idle Clients

5.2.1 CPU Load

When looking at the results found in subsection 4.2.1, all three transports perform very good, keeping the CPU usage low, even as the client count increases to 500. Even though the three different servers all perform nicely, the WebSocket server uses less than half the CPU cycles the other two servers does. Never once does it exceed 1% of CPU use, while the Long Polling and Server Sent Events servers always lies between 2 and 3 percent. The fact that the HTTP Long Polling and Server Sent Events servers perform very similar here can be explained by the fact that they both run on top of the same Express[31] server.

These are certainly good results, but in fact they are totally expected. Even though 500 standalone clients was the maximum my client computer could handle, 500 connections is not a lot for a server to handle.

5.2.2 Memory Footprint

Here we look at the results found in subsection 4.2.2.

The memory footprint of the three servers start out differently. The WebSocket server starts with a memory footprint of 17MB for 1 user, while the Long Polling and Server Sent Events servers both start out at 28MB. Once again, the similarities between the two latter mentioned servers can be explained by the case that they both use the same web application framework, Express. The WebSocket server on the other hand uses the very bare bones WebSocket library ws[32] and it clearly has a very small memory footprint.

As the number of connected or polling clients increases, the WebSocket server's memory footprint increases faster than the other two servers and around 400 clients it catches up to the other two servers. This is expected as WebSocket is a stateful protocol, requiring a larger memory footprint for each connection. While, this is also to some degree true for Server Sent Events, the "connection" is more lightweight. The penalty in memory consumption by using WebSocket is visible, but not too expensive. Overall, these results are expected, but nevertheless good.

5.2.3 Response Time

The discussion here is aimed towards the results presented in subsection 4.2.3.

The response times for all three servers is really good here and always way below the 0.1 second limit from Nielsen. Once again we see the HTTP Long Polling and Server Sent Events versions are very close to each other while the WebSocket version outperform them both. The WebSocket server always respond within 1.3 to 1.5 milliseconds, while the other two generally uses 3 milliseconds. The similarities between the Long Polling and Server Sent Events servers can once again be explained by the common Express server, and also by the fact that these two tests use the same HTTP based ping client. In contrast, the WebSocket server uses a different standalone WebSocket based ping client. Once again, we see the WebSocket server come out on top.

5.3 Load Testing

The discussion in this section is aimed towards the *load testing part* of the test. That means the part of the results where the CPU utilization is below maximum. Because some of the servers started to behave unexpected during stressing load levels, the separation between load and stress tests have been created. The result analysis from the stress test is found in section 5.4.

5.3.1 Test scenario 1

In this subsection I look into the response times for the first test scenario during its broadcast phase. Figure 34 shows the same results found in subsection 4.3.2, but this time with the 1.0 and 0.1 second limits by Nielsen.

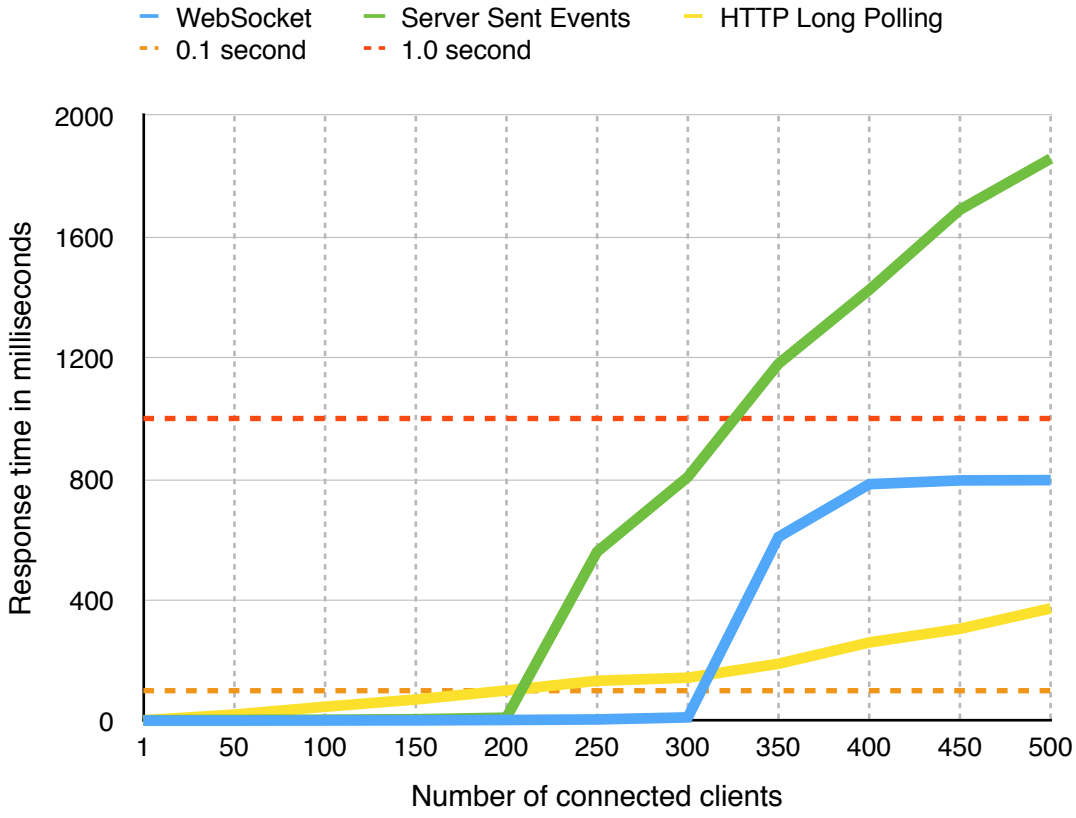


Figure 34: The response times during the first test scenario's test phase

Immediately, it looks like Long Polling severely outperforms the WebSocket and Sever Sent Events versions. However, since this section only looks into the load test part of the results, we must ignore the part where the server is stressed.

Figure 35 shows the same results, this time zoomed in to show a maximum of 110 milliseconds on the Y axis and 200 clients at the X axis. The reason behind this is that with 250 clients the Server Sent Events server met its break point - and the load test turned to a stress test. One could argue that the HTTP Long Polling server is always being stressed as the CPU utilization reaches 98% with just 50 clients, but still the increase in response time grows gradually and not sudden as with Server Sent Events and WebSocket.

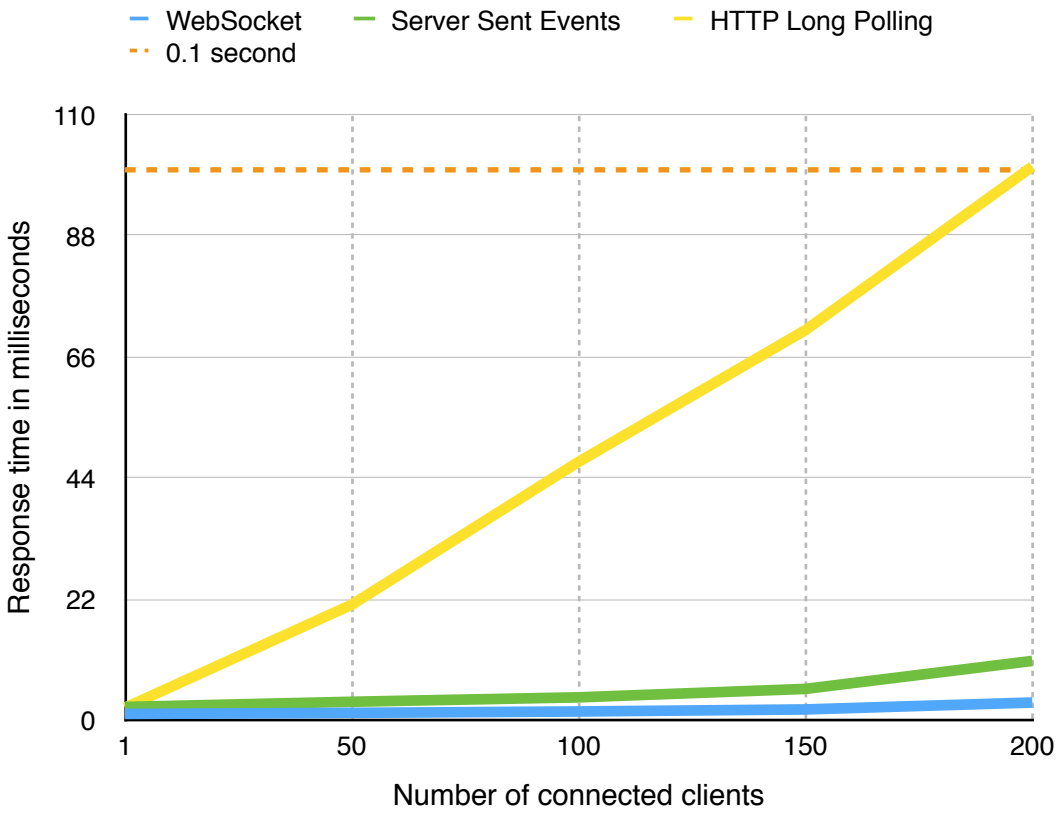


Figure 35: The response times during the first test scenario's test phase

Now, a totally different picture emerges. Here both WebSocket and Server Sent Events totally dominates the Long Polling server in terms of response time, and you can see them staying almost flat and always way below the 0.1 limit from Nielsen. The HTTP Long Polling server has an gradual and almost linear growth in response time.

These results are expected. WebSocket should outperform both the other two servers and, while being stressed, the Long Polling version sees an almost linear growth as the client count increases. The fact that the Long Polling version reaches stressing levels way before the other two servers is also expected. As discussed in the background chapter, HTTP is not designed for this type of real-time behavior, requiring a request for each server update.

From Kristian Johannessen's thesis Server Sent Events was expected to perform quite comparable[29] to WebSocket, and that is the case with these results. Being based on HTTP and not being a new standalone protocol, Server Sent Events performs very well.

5.3.2 Test scenario 2

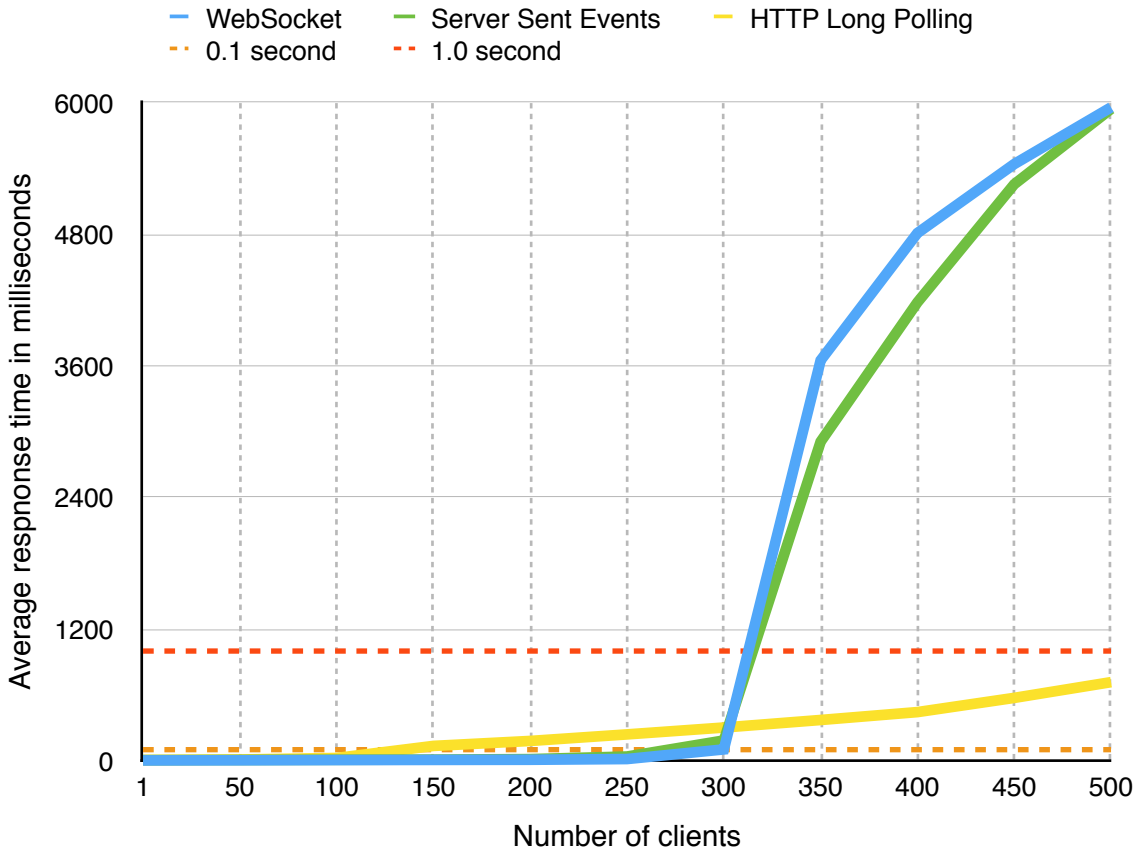


Figure 36: The response times during the second test scenario's test phase

The graph in figure 36 is the exact same graph that was presented in subsection 4.4.2, but this time with lines representing the 0.1 and 1.0 second limits by Jakob Nielsen. Straight away, it once again looks like if Long Polling devours the other two servers in terms of response time. That is true as well, and even more so this time than in the first scenario. However, as this section looks into the load part, not the stress part, we must cut out the part where CPU utilization is at a maximum.

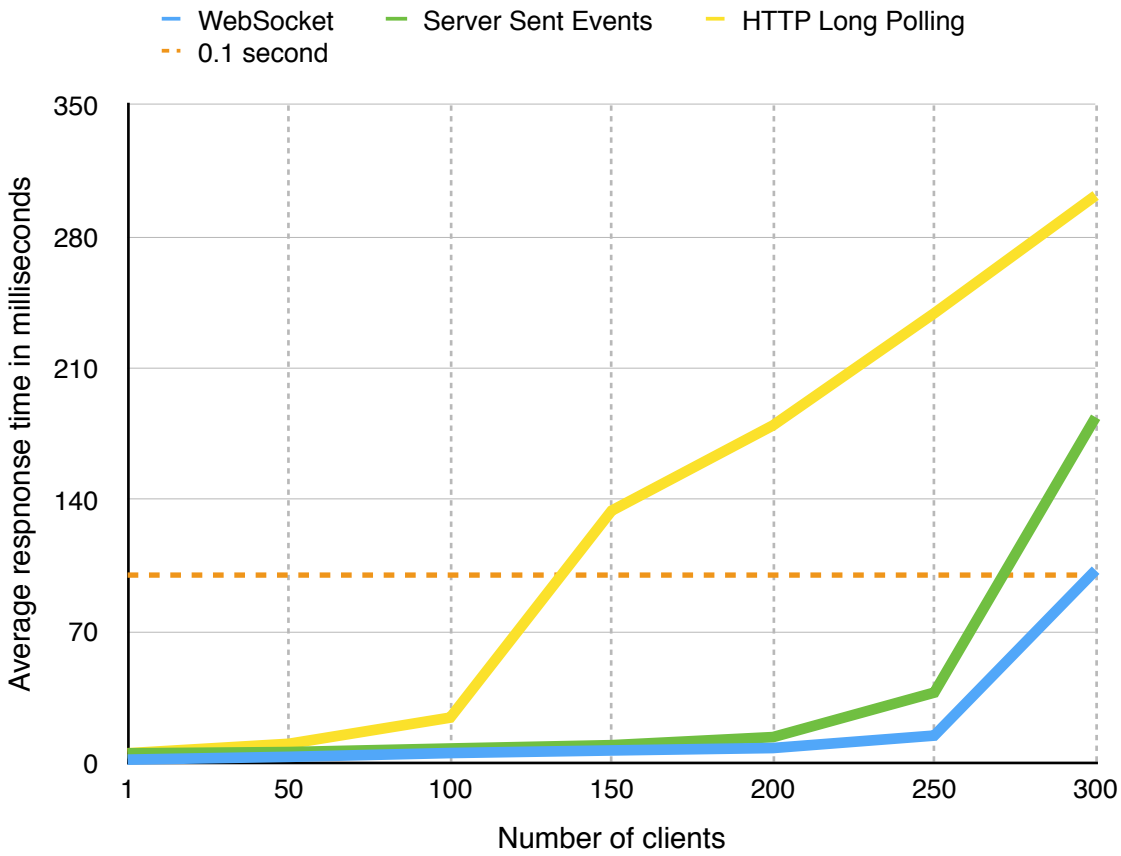


Figure 37: The response times during the second test scenario's test phase

Both the WebSocket and the Server Sent Events servers reaches their maximum CPU utilization at the 350 connected client mark, so I have decided to cut out the part with 350 and more clients. Once again, it must be noted that the HTTP Long Polling server reach its maximum CPU load ahead of the other two servers, at 150 clients. Even though it does, it doesn't seem to have the same explosive growth in response time as the other two servers. As with the first test scenario, this one shows how much better the Server Sent Events and the WebSocket servers perform compared to the HTTP Long Polling counterpart, when the load is less than full. The two best performers are almost identical up until 200-250 clients, where we see them diverge a bit. At this point it is becoming apparent that they are affected by the high levels of load and the response time begins to increase rather fast.

The fact that HTTP has no built in mechanism for real-time behavior and the increase in architectural complexity for the Long Polling server (see subsection 3.7.4), made me expect it to be outperformed. What I didn't expect to see though, was how well the Server Sent Events server performed. I expected WebSocket to be the clear winner here, as the protocol works bidirectionally, but even with the Server Sent Events server requiring a separate HTTP route for the incoming messages, it performed very well.

5.3.3 Load Test Summary

- The HTTP Long Polling server reaches maximum CPU load way before the other two servers and the response time grows linearly as the client count increases.

- When the Server Sent Events and WebSocket server reaches full CPU utilization, their response times goes through the roof. This is seen as an anomaly, and will be discussed in the two following sections.
- As long as the load levels are below maximum, all three servers perform quite well, always staying below the 0.1 second Nielsen limit.
- As expected Server Sent Events performed well in the first scenario, as the messages are server-to-client only.
- Unexpectedly, Server Sent Events performed very good in the second scenario, even though it required a second HTTP route for incoming chat messages.
- WebSocket is the real winner here, having the lowest response times throughout the whole load tests. This was expected though.

5.4 Stress Testing

5.4.1 Test Scenario 1

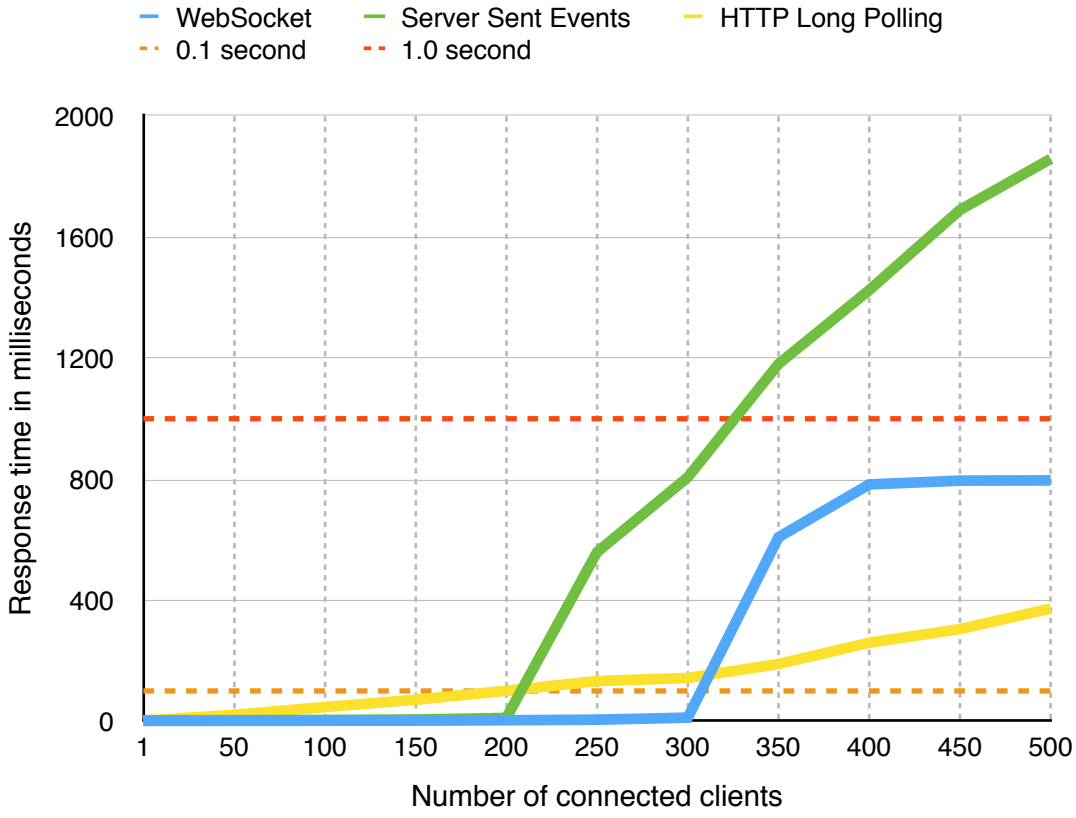


Figure 38: Response times during the broadcast phase in test scenario 1

The Long Polling server was expected to reach max CPU utilization before the other two servers because of its architectural complexity. That expectation was correct, with the HTTP Long Polling server reaches its CPU utilization peak at just 50 clients, while the Server Sent Event and WebSocket servers reaches CPU peak at 250 and 350 respectively. It was also expected that WebSocket would perform better than Server Sent Events overall, as the protocol was built to be efficient. But the way the different servers performed after reaching CPU peak, was totally unexpected.

The HTTP Long Polling server has a gradual and steady increase in response time as the client count increases. It performs actually really well and stays below the 1.0 second Nielsen limit at all times. It does however breach the 0.1 second limit at the 200 client mark.

The Server Sent Events server performs, as previously stated, great while the load is moderate, but when CPU peak is reached, the picture changes quickly. The response time explodes to the roof, and at the 350 client mark, breaks the 1.0 second limit. With 500 connected clients, the Server Sent Events server use a whopping 1,8 seconds to answer the ping client.

Similar to the Server Sent Events server, the WebSocket counterpart also experience an explosive growth in response time when the CPU is brought to stress levels. Interestingly the response time seem to stabilize just under 800 milliseconds ensuring it stays below the 1.0 second limit throughout the whole test scenario.

The sudden spikes in response time found with the Server Sent Events and WebSocket servers were not predicted. A more gradual and almost linear growth in response time, like with the Long Polling server, was expected. Plausible explanations for these anomalies will be discussed in section 5.5.

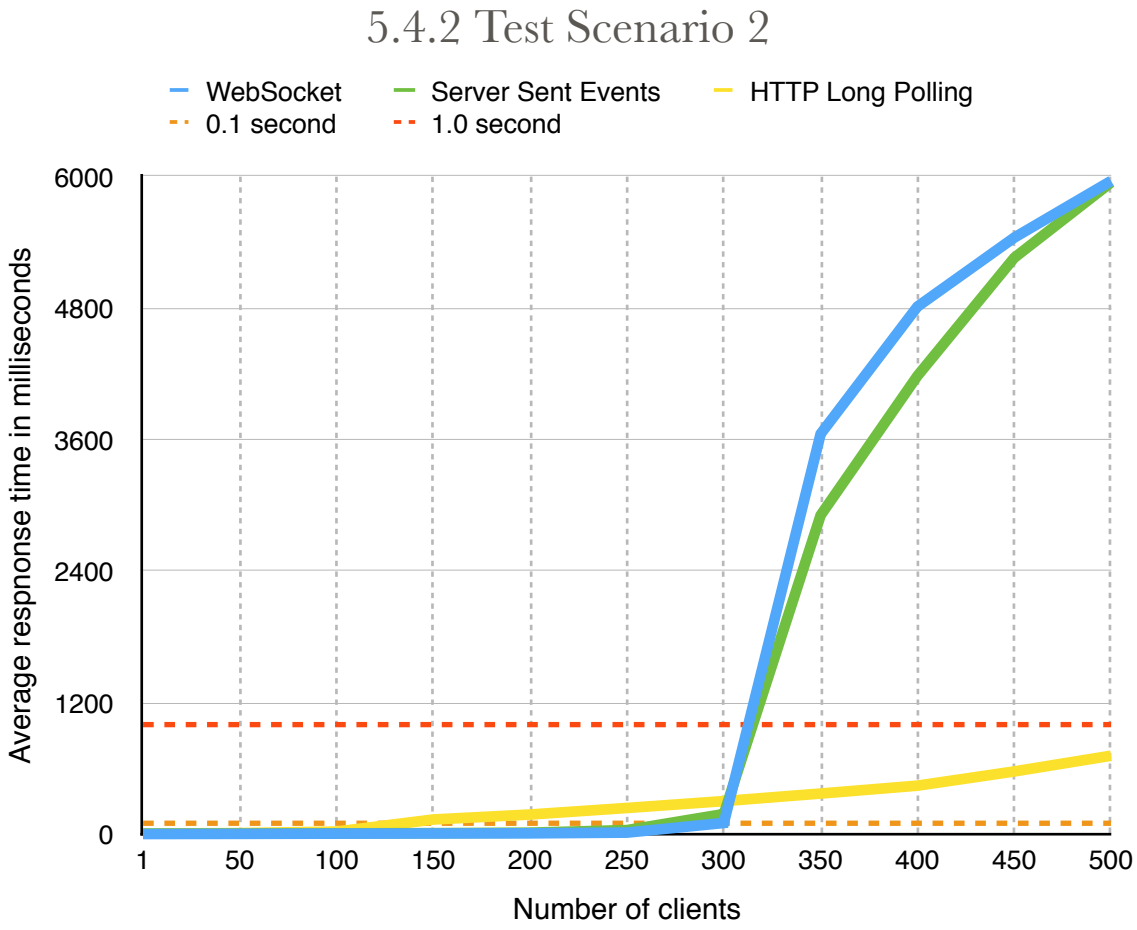


Figure 39: Response times during the chat phase in test scenario 2

It was expected that the HTTP Long Polling server would reach maximum CPU utilization before the other two servers. This proved to be an accurate expectation, as it reached full CPU use with 150 clients, while the Server Sent Events and WebSocket servers managed to reach 350 clients before seeing the same CPU load levels.

Just as with the first test scenario, it was assumed that the increase in response time when stressing the server, would be linear. Once again it proved to be right for the HTTP Long Polling server, while the other two servers, saw their response time increase dramatically when stressed and skyrocket way above the HTTP Long Polling equivalent. In this scenario it is only the Long Polling server we see stay below the 1.0 second Nielsen limit. The other two servers reaches response times of nearly six times that limit.

Once more, it must be stated that these results are very interesting, and maybe more surprising than the results for the first scenario. The chat application was a perfect fit for WebSocket with native bidirectional messaging support. The Server Sent Events counterpart was architectural more complex and the Long Polling version even more so. The increase in architectural complexity does not seem to handicap the servers, as the worst performer here is the WebSocket one.

5.4.3 Stress Test Summary

- Once the Long Polling servers are stressed, the response times behaves expectedly and increases linearly with the client count. In both scenarios, they breach the 0.1 second Nielsen limit while stressed, but always stay below the 1.0 second limit.
- Both the WebSocket and Server Sent Events servers experience an unexpected explosive growth in response times when the CPU is stressed. A linear Long Polling like growth was expected as the client count increases. The sudden and dramatic increase must be considered an *anomaly* and can be an issue with the software platform. Possible explanations will be presented in the following section.
- The anomalies cannot be ignored, pointing to a clear win for HTTP Long Polling.

5.5 Memory and Response Time Anomalies - Possible Issues With the Software Platform

I did not focus much on memory when implementing the test scenarios, but decided to record memory consumption before and after the test, to see if there were any unexpected results - anomalies. It was expected that the memory consumption would gradually and linearly increase as the client count grew. The increase would mainly come from two factors:

- The server needs memory for each connection.
- The server receives messages that are temporarily or permanently stored in memory. Temporarily for the Server Sent Events and WebSocket servers, and permanently for the Long Polling server. (See the example in figure 6 in subsection 2.4.1 to understand why).

The Server Sent Events and WebSocket servers was implemented to quickly discard each received message, but it has to be stored in memory before the garbage collector flushes it. With no easy way to inspect how the Node.js garbage collector (more explicitly, Google's V8 JavaScript engine) works or when it runs, it was hard to tell whether there would be a significant difference between the three servers, even though the Long Polling version stored each received message.

Because of these uncertainties regarding the memory inspection as well as the garbage collector, I did not want memory to be a main focus for this thesis. Thankfully I did inspect memory consumption after the tests though, as the results can point to explanations for why the response times suddenly goes through the roof.

Following in figure 40 and 41, you can see the memory consumption right after the tests have finished. In the first scenario depicted in figure 40, you can see that when the Server Sent Events and WebSocket servers reaches full CPU utilization with 250 and 350 clients respectively, the memory footprint increases dramatically. Both consume well over 1 GB of memory with 500 clients. The expected results would be lower and along the line of the Long Polling server, that lands on 97 MB, more than 10 times lower.

In the second test scenario, found in figure 41, we see the same story, although not in the same magnitude. When the Server Sent Events and WebSocket servers reach full CPU utilization at 350 clients, there is a bump in memory usage with the WebSocket version being the most notable.

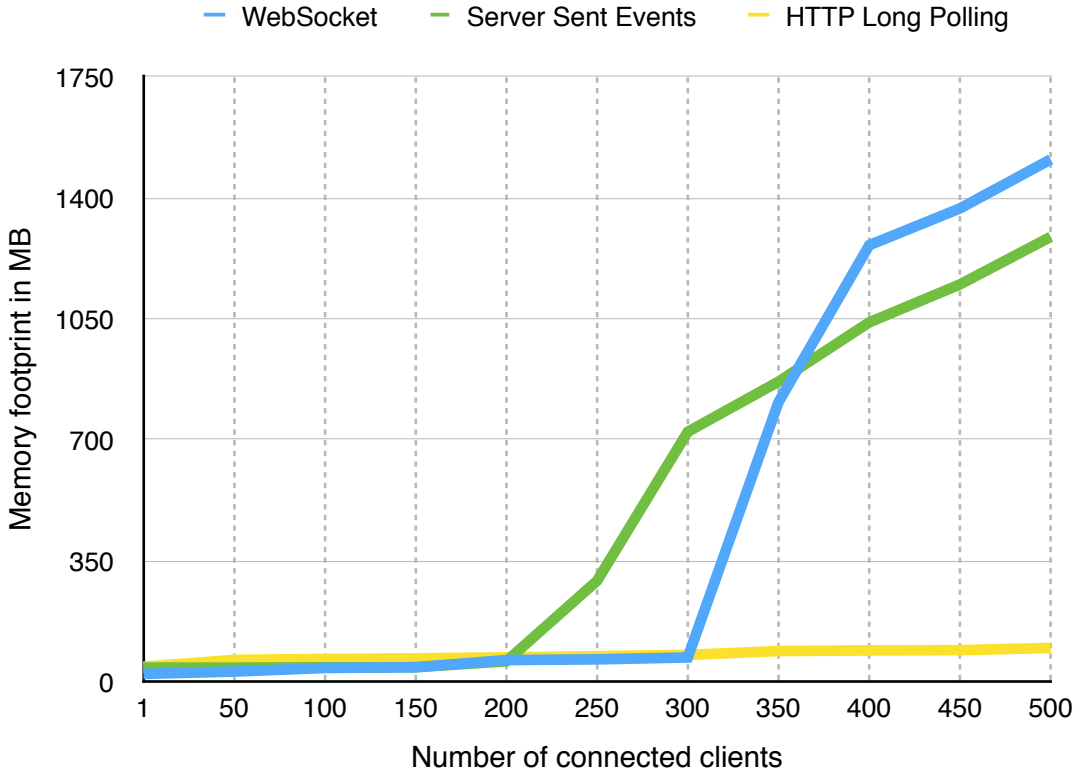


Figure 40: Memory footprint right after the broadcast phase in test scenario 1

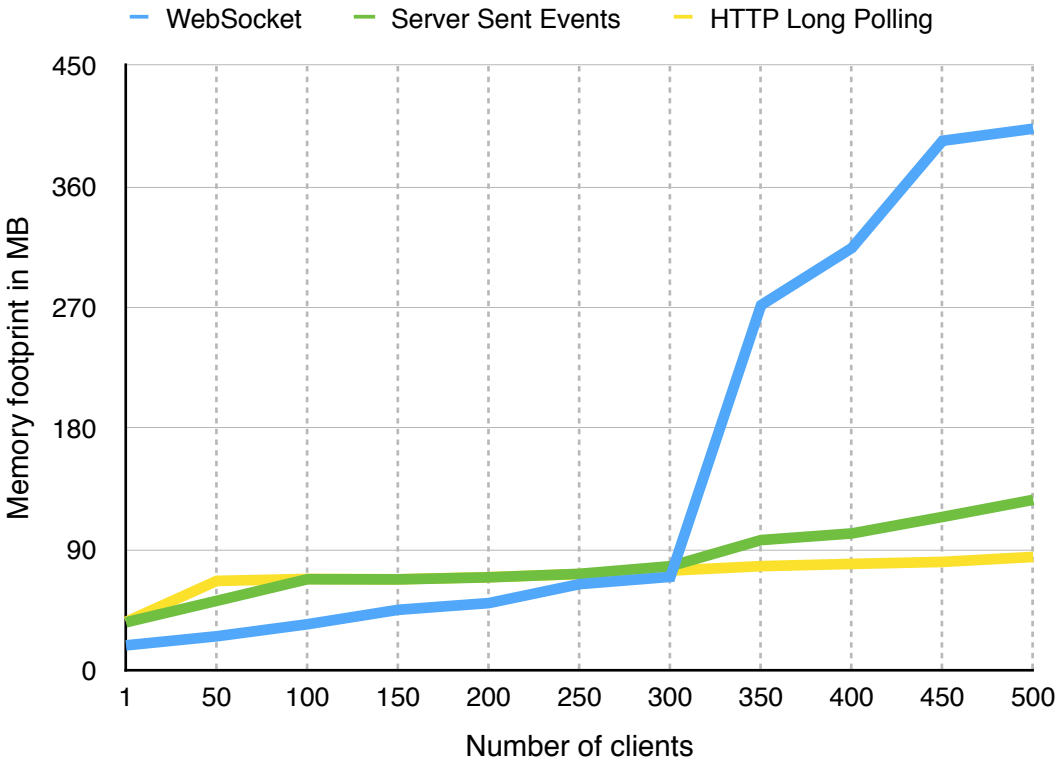


Figure 41: Memory footprint right after the chat phase in test scenario 2

The dramatic increases in memory footprint we see here are comparable to the sudden escalation we see with the response times and both happen when the CPU is stressed very hard. In both test scenarios, the three different servers are developed using the same techniques and code styles, so there are really no reason for these sudden spikes in memory and response times to happen. Consequently the possibility of a bug in Node.js or one of the libraries in use became a reality.

For the rest of this section, I will list and discuss possible explanations to why these unanticipated spikes occur.

5.5.1 Issue With the WebSocket Implementation

The WebSocket servers are the ones that are most affected by this anomaly, as the spikes in response time and memory occur in both test scenarios. This makes it possible that there is a bug or issue with the WebSocket library that was used. The version of ws used in the tests is *0.4.32* and as of 29th of March 2015, *0.7.1* is the latest. When looking at the change logs for version *0.5* (the version after 0.4.32) arriving November 20th 2014, there are two very interesting changes to the library: "*Fixed a file descriptor leak*" and "*Fixed memory leak caused by EventEmitters*"[33]. Memory leaks can cause the garbage collector to become more aggressive[34], meaning increased CPU use. If these issues did occur in my tests, they could explain the high response times and large memory consumption during high load, at least for the WebSocket version.

5.5.2 Node.js

As stated in subsection 3.7.1, I chose to implement the Server Sent Events server myself. Interestingly, this means that there are no difference in libraries used by the Server Sent Events server and the Long Polling twin (true for both test scenarios). Why then would the increase in response time and memory footprint only happen with the Server Sent Events version?

Looking for bugs or issues in the Node.js source code would take very long time and is way out of the scope for this thesis, but it is possible that there is an issue with the Node.js version used in these tests. As a consequent of being a new, innovative and fast moving platform, Node.js can suffer from bugs and instability.

Since I settled on version 0.10.35, there has happened a lot in the world of Node.js. Late last year, the open source community forked Node.js into io.js[35] after being dissatisfied by how Joyent, the organization behind Node.js, ran the project. io.js includes an updated version of the Google V8 JavaScript engine. Soon after, Joyent released Node.js version 0.12 with the same updated V8 engine. Maybe this new engine running in io.js or Node.js 0.12 fixes the test anomalies.

5.5.3 HTTP Is More Tested and Stable

A possible explanation to why there could be one or more bugs with the implementation, is the fact that HTTP is much more tested and in use than the other two approaches. Also, it is very rare that you push a server to the absolute limits in real world use. Maybe these abnormalities have never been seen before.

5.5.4 Errors with the Test Implementation

It is also possible that there are errors in my own code. Writing bug free code is proven to be difficult, and especially when there are few people testing the code. I do however not believe this is the case. As long as the CPU load is moderate and below maximum, nothing out of the ordinary happens. It is only when the CPU is stressed really hard, that the anomalies and unexpected results appear. For this reason I think it is safe to say that if there is a software error causing these anomalies, that error is likely not in my code.

5.5 Implementation

Up until this point, all discussion has been related to the test results. How different technologies compare in performance is of course very important, but how easy they are to handle for a programmer is also an area of great importance. In this section I will discuss how the different servers were to implement from a programmer's perspective.

5.5.1 Test Scenario 1

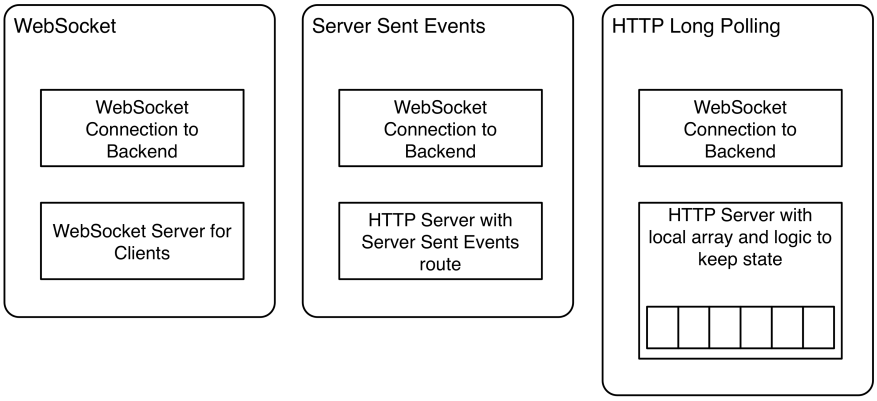


Figure 42: The three different servers in the first test scenario

Figure 42 shows the different components involved in the three different servers for the first test scenario. Obviously they all need a WebSocket client connection to the backend WebSocket server, so that component is common among the three versions.

Both the Server Sent Events and WebSocket servers were straightforward to write. The two technologies both support the concept of a persistent connection, so there were no need to store incoming backend messages on the server - they could be broadcasted right as the server received them.

Standard HTTP, on the other hand, has no way to keep the connection open for more than one reply after each request. This means double the network traffic and increased complexity on the server. As seen in figure 6 in subsection 2.4.3, the Long Polling server must locally store each broadcast message to ensure that all clients receive them. This means a quite substantial increase server complexity, but also on the client side. Each client must keep track of what messages it got and then tell the server what the last message it received was.

5.5.2 Test Scenario 2

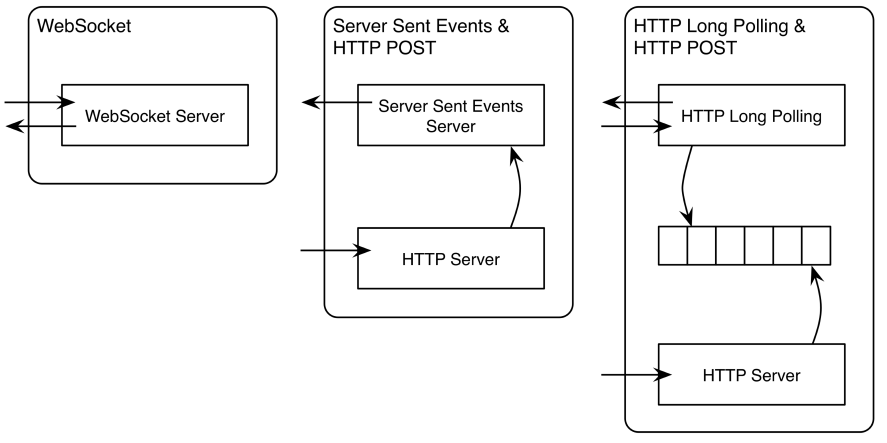


Figure 43: The three difference servers in the second test scenario including arrows for incoming and outgoing messages.

Looking at figure 43, the difference in server complexity between the three servers becomes really apparent. WebSocket is the perfect transport for the second scenario, where messages are going in both directions, server-to-client and client-to-server. As WebSocket is a full duplex protocol, the server can be very simple, with one component for both incoming and outgoing messages. Conceptually simple and easy to program.

Server Sent Events for outgoing and an additional HTTP POST route for incoming chat messages proved to be a great combo. Because Server Sent Events allow us to keep track of connections, it was easy to distribute chat messages as soon as they were received. Conceptually a bit more complex than the WebSocket server, but not by much.

The Long Polling server was the most complex to write. First, you need one HTTP POST route for incoming chat messages. Then, you need an additional route where the clients can poll chat messages. Lastly, as figure 6 in subsection 2.4.3 proves, you need a local buffer where all messages are stored (at least temporarily) to ensure that every client get them all. Conceptually more complex and more difficult to develop.

5.5.3 Summary

- If there only is a need for outgoing server messages, Server Sent Events is just as simple to use as WebSocket.
- If the is a need for both outgoing and incoming messages, WebSocket is clearly the easiest pick, as the protocol is full-duplex by nature. However Server Sent Events plus an additional HTTP route for incoming messages is also easy to grasp.
- Using only HTTP is conceptually more complex and requires some work around to make up for the fact that the protocol is stateless.

5.6 Conclusion

Her må jeg svare direkte på problemstillingene. 0,5 til 1 side er nok.

5.7 Further Work

HTTP 2.0
WebRTC
Samme oppgave på flere software platformer

1 til 2 sider.

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Appendix