Real-Time Web with WebSocket

A Comparison of Real-Time Technologies for the Web

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1 Introduction

1.1 Real-Time Web

The web started out as a simple document sharing service to make the lives of researchers at CERN simpler. The transformation from then, to the web rich and dynamic web today, is quite amazing. Today, there are only small differences between applications running locally on your device and applications running in a web browser - web applications. Part of what makes this possible is the fact that the web has become real-time capable. The real-time web makes it possible for a website to dynamically update itself when new content is available.

HVA ER REAL-TIME?

To better understand what is meant by the term real-time in this thesis, consider the following two examples.

1. A stock price application where several clients are connected to server. This stock price server subscribes to a broker backend for updates on stock prices. When the stock price server receives price updates from the backend, it broadcasts this to all clients.
2. 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.

The first example requires unidirectional messaging, with messages (stock prices) only going from the server to the clients. The second example is bidirectional, requiring both server-to-client and client-to-server messages. These two examples show the types of real-time applications this thesis focuses on.

1.2 Research Questions

Making the web real-time was not straightforward, because HTTP, the original web protocol, did not natively support real-time behavior. But today, there are several new technologies available to make real-time apps possible, like HTTP based *Long Polling* and *Server Sent Events*. In addition there is the new protocol *WebSocket*. WebSocket is a very thin application layer skin on top of TCP, allowing for a full-duplex data pipe on the web. In this thesis these three different technologies will commonly be referenced as different *transports*.

FLYTTE DETTE TIL INTRO?

In addition to the two real-time application types above, there is peer-to-peer. With WebRTC[1] peer-to-peer is possible on the web as well. However, as of this writing WebRTC was not fully standardized, so it was decided to not include WebRTC in this thesis.

In this thesis I will look at WebSocket and compare it to the two HTTP real-time transports Long Polling and Server Sent Events. I will compare them based on two criteria. First and foremost their performance is considered. Then, I will discuss differences from a programmer's perspective.

I have formed the following research questions for this thesis:

1. For what types of real-time web applications does WebSocket provide a benefit over Long Polling and Server Sent Events?
2. How does WebSocket perform compared to Long Polling and Server Sent Events in an unidirectional messaging setting with high levels of load?
3. How does WebSocket perform compared to Long Polling and Server Sent Events in an bidirectional messaging setting with high levels of load?
4. Does WebSocket provide any advantages over Long Polling and Server Sent Events from a programmer's perspective?

The first question is the main research question and the following three are meant to validate and substantiate it.

The main research question demonstrate my expectation that WebSocket is going to perform better than the other two technologies. That expectation derives from the results found in Kristian Johannessen's 2014 master's thesis[2]. In fact, many of the choices made in this thesis is based on the work by and suggestions from Johannessen. Kristian's thesis and other related work is presented at the start of the Background chapter.

1.3 Outline

Chapter 2 - Background

Chapter 2 presents all background material needed to understand the methodology and research part of this thesis. That means all three transports, the chosen software platform and a quick note on performance testing. Previous and other relevant academic work is also presented here.

Chapter 3 - Methodology

Based on the background material, I have developed two distinct real-time scenarios to compare the three different transports. This chapter presents these two scenarios and discusses parameters and choices. How the test results are retrieved is also discussed.

Chapter 4 - Results

In this chapter, the results will be presented as they were found when testing. The results are not discussed or analyzed before chapter 5.

Chapter 5 - Discussion

This chapter includes detailed analysis and discussion of the results from the previous chapter. Any abnormalities will be explained with their possible reasons. This chapter also includes the thesis conclusion, where I directly answers the research questions. Lastly, there is a section on suggestions for further work.

The thesis is concluded by a reference list and an appendix.

2 Background

2.1 Related Work

In the 2007 paper[3] by Bozdag, Mesbah and Deursen, different real-time techniques for the web is compared. The two techniques in question is server pull and server push. Server push means that server updates are pushed from the server to the client, while server pull means that the client actively asks (pulls) for updates. The authors conclude with praise for the push approach if high data coherence and network performance is desired. But they do point out some problems with regards to scalability. The push approach they recommend is HTTP-streaming. Server Sent Events and WebSocket are other push approaches, but are not mentioned, as they did not exist at the time when the article was written.

The bachelor's thesis by Johvik, seems to be heavily inspired and motivated by the work of Bozdag, Mesbah and Deursen. In it Johvik determines that the pull based HTTP Long Polling technique is better than HTTP-streaming, conflicting with the views of the previous article. WebSocket did exist at the time of the article's writing, but Jorvik decided not to include it.

Then, there is the master's thesis by Kristian Johannessen[2]. Much of this thesis is based on the work and suggestions from his 2014 thesis. In the first part of his thesis he compares different real-time frameworks for the web. Some frameworks such as SignalR and Lightstreamer, support several real-time transports, like Server Sent Events and WebSocket. Some even provide fallback solutions to support the largest possible set of clients. Based on performance and programmer friendliness, he recommends SignalR as the best real-time framework, closely followed by Socket.IO.

The second part of his thesis compares WebSocket to traditional HTTP techniques for real-time behavior. He concludes by saying that "…WebSocket is better than HTTP in every aspect of real time applications….", although he is pleasantly surprised by how well Server Sent Events performs for server-to-client communication.

He met challenges when using full fledged web browsers as clients and consequently advised me to use smaller, lightweight command line clients for my tests. Because he chose to use web browser clients, he could not focus on scalability and see what happens when the transports behave when the servers are stressed hard.

Based on his recommendations and inspiration from his thesis, I came up with a similar by yet distinctly different thesis. I wanted to focus solely on the transports - not the frameworks. I also wanted to use smaller command line clients that lets me spawn them in the number of hundreds and see how the server behaves when pushed to the limit.

The rest of this chapter includes all the technologies I had to learn before creating my test scenarios. That includes the protocols HTTP and WebSocket, as well as HTTP techniques like HTTP Long Polling for real-time behavior. Node.js, the chosen software platform is also presented. Lastly, a section on performance testing.

2.2 Introduction to the 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 a 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 this thesis will reveal, it is hard and suboptimal to develop real-time apps using HTTP.

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, bringing TCP like networking to the web.

2.3 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 designed as a 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 to be stateless. Every connection is treated the same way.

The 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 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[4].

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»[5]. 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 when a user wants to submit data to the server. 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 figure below shows the entire GET request a web browser sends when going to www.uio.no. The web browser adds several header fields:

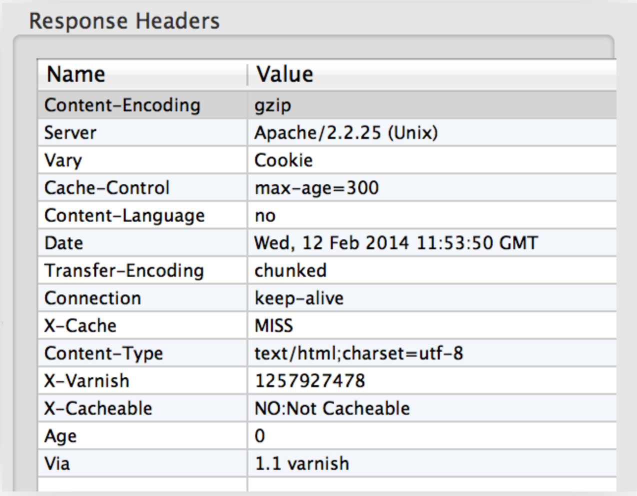
Request Headers

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[6].

As you can see above, there is 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, while the Accept header tells the server what file types the client can read. HTTP Headers are an important part of the protocol and adds a slight sense 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.[6]

Considering that http://www.uio.no is a typical web site,

NO!!

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.

2.4 Modern Web

As mentioned, HTTP was designed to serve static hyperlinked documents. Today however, you rarely 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 from 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.

Essential to this development was how HTTP was used in order to achieve real-time behavior - Ajax, and the new HTML standard - HTML5.

2.4.1 HTML5

HTML5 is the fifth revision of the HTML markup language and the first major update since HTML4 was standardized in 1997[7]. Even though HTML5 adoption stated many years ago, the W3C recommendation was just recently finalized[8]. HTML5 is, despite its name, much more than just an updated HTML version. It is a collection of many technologies that is 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 is possible to build applications that resemble their platform native counterpart, right in the browser. And with tools like PhoneGap[9] and Cordova[10], it is 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.

2.4.2 Ajax

Ajax as a term was introduced by Jesse James Garret in 2004, when he wrote "Ajax: A New Approach to Web Applications"[11]. 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[12]. 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[13] 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 heart of web apps, and it brought interactivity to an otherwise static web. Together with some clever techniques, the web becomes real-time.

2.5 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.

2.5.1 HTTP Polling

The first solution is a client side JavaScript timer 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.

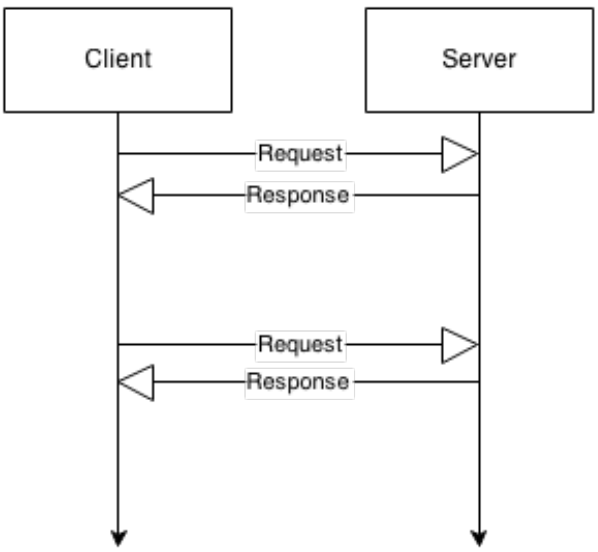


Figure 4: HTTP Polling example

2.5.2 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 behavior only using existing HTTP technologies. The two most used ones 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[3]. Long Polling gives the user the impression of having data pushed from the server, even though it in theory is not.

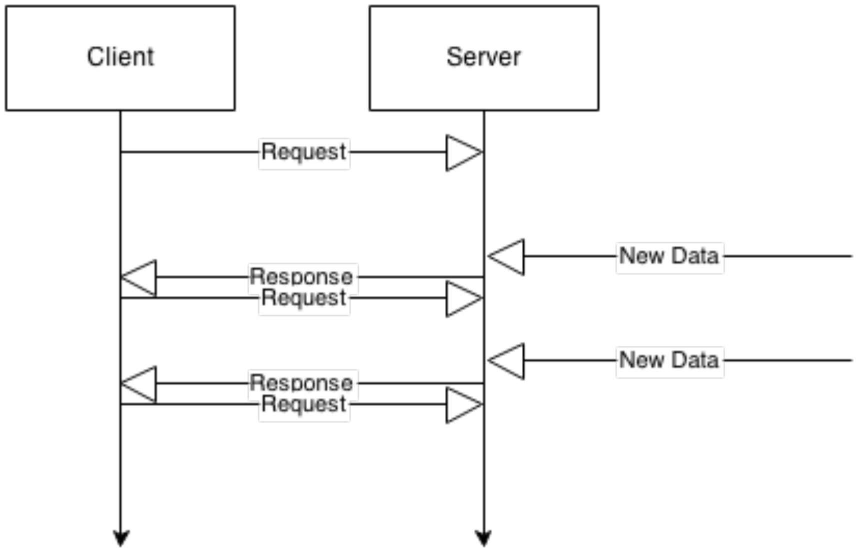


Figure 5: HTTP Long Polling Example

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.

2.5.3 Why Comet and HTTP is Unsatisfactory

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 the scripts 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.

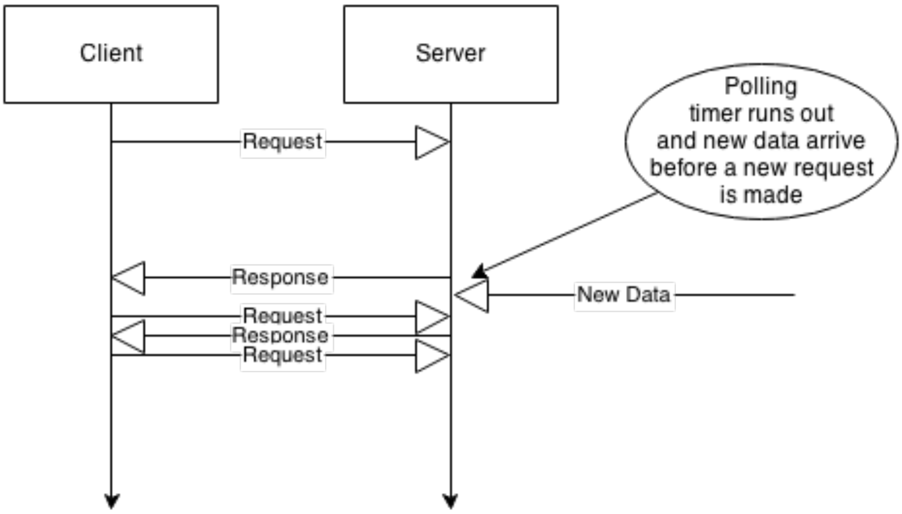


Figure 6: Example of client side outdated data with Long Polling

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*. With many real time applications you only want to send small messages, maybe just a couple of bytes. This vast amount of unnecessary header data is repeated for each packet and could cram the network.

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

Even though Long Polling and HTTP Streaming accomplishes push behavior, there are several disadvantages to using the two techniques. Compared to the lower level more powerful TCP sockets, building real time networked applications for the web introduces various obstacles.

Because of the lack of native real-time capabilities in HTTP, HTML5 introduces Server Sent Events and WebSocket.

2.6 Server Sent Events

Server Sent Events solves the issues with server push we saw with Long Polling and Streaming. It is an extension of HTTP and it provides the concept of a connection. As its name implies, Server Sent Events supports only server-to-client messaging. To understand Server Sent Events, you must understand the EventSource API and the Event Stream Protocol.

2.6.1 EventSource API

```
[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[14].

The EventSource API is small and simple, yet powerful. It provides different ready states (*CONNECTING, OPEN* and *CLOSED*) to make the connection stateful. It also provides three events a can listen for (*open, message* and *error*). A simple close method is added for connection teardown. Server Sent Events built for server-to-client messaging only, so there are no send method, as we see with WebSocket later. 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

Under the hood, 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[15].

Syntactically, what makes Server Sent Events different 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[15].

In the example above you can see how the server sets the client reconnect interval to 15 seconds. The examples also shows that data the data format can be pure text or JSON. Other features include the ability to set an id and a custom event associated with a message.

2.6.3 Server Sent Events Adoption

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 it, 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 has to be converted using base64 encoding. This adds some overhead. Second, the 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.

While many apps would benefit from server push with Server Sent Events, some apps require client-to-server messaging. Server Sent Events has no answer to that problem. That is left for WebSocket to solve - the full-duplex TCP like protocol for the web.

2.7 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[16] 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[17]) and the API.

FORKLARE MER HVA WEBSOCKET FAKTISK ER

2.7.1 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 executable code. 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.

2.7.2 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 need to 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 a 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 is triggered, and 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[18]

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 with 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:

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-------+-+-------------+-------------------------------+
|F|R|R|R| opcode|M| Payload len |    Extended payload length    |
|I|S|S|S|  (4)  |A|     (7)     |             (16/64)           |
|N|V|V|V|       |S|             |   (if payload len==126/127)   |
| |1|2|3|       |K|             |                               |
+-+-+-+-+-------+-+-------------+ - - - - - - - - - - - - - - - +
|     Extended payload length continued, if payload len == 127  |
+ - - - - - - - - - - - - - - - +-------------------------------+
|                               |Masking-key, if MASK set to 1  |
+-------------------------------+-------------------------------+
| Masking-key (continued)       |          Payload Data         |
+-------------------------------- - - - - - - - - - - - - - - - +
:                     Payload Data continued ...                :
+ - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - +
|                     Payload Data continued ...                |
+---------------------------------------------------------------+
```

Figure 10: The WebSocket frame as defined in RFC6455[17]

- 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[19], such as Microsoft SOAP and unofficial open protocols such as XMPP. There is possible for anyone 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
```

2.7.3 WebSocket Libraries and Deployment

All modern web browsers support WebSocket, but there are sadly still lot a users running out of date browsers. As a result of that, it can be beneficial to use a WebSocket emulation library. A WebSocket emulation library is a piece of software that seamlessly switches to other transports if there is no WebSocket support. All this is done in the background and only exposing the programmer for a single interface. There are many options available, but the two most notable are Socket.IO[20] and SockJS[21]. Their fallback transports includes Long Polling, HTTP Streaming and even Adobe Flash Sockets for Socket.IO. SockJS tries to emulate the WebSocket API as closely 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[22]. On the .NET side there is SignalR[23] 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[24].

2.7.4 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.

2.8 Node.js - JavaScript Everywhere

As advised by Kristian Johannessen, I chose to develop test scenarios and do performance testing on a single platform. That choice fell on Node.js. Reasons why is discussed in the Methodology chapter.

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[25], CoffeeScript[26] and TypeScript[27], 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++[28], 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[29]. 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.

2.9 Performance Testing

Because this thesis will be about benchmarking technologies, it is appropriate to introduce some basics of performance testing. It has become increasingly more important to performance test your system. Today, 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"[30]. 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 the most efficient solution 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.

In this thesis, WebSocket, Server Sent Events and HTTP Long Polling will be load and stress tested. The tests will start out as load tests, with a small number of connected clients and moderate server load. As the number of clients grows, so should the server load. When the server reaches full CPU utilization, the load test transforms to a stress test. This point is the *break-point*.

3 Methodology

3.1 Introduction

I have created two test scenarios to performance test WebSocket, Server Sent Events and Long Polling. The thesis introduction presented two types of real-time applications - the stock price example as a unidirectional messaging application and the chat application as a bidirectional messaging system. These two examples are the basis for the two test scenarios I've created. Each test scenario has three implementations, one powered by WebSocket, one by Server Sent Events and one by HTTP Long Polling.

The first test scenario is a broadcast application where a given number of clients connects to a server. This server receives incoming messages from an independent backend component. When the server receives these messages, it immediately broadcasts them to the connected clients. In a sense, this is the stock price application.

The second test scenarios is a chat application. It consists of a given number of client that connect to a server. Each client periodically sends chat messages to the server. The server then broadcasts these messages to the clients, as the come in. Naturally, with HTTP being unidirectional, this scenario needs another component for client-to-server messages for the Server Sent Events and Long Polling versions.

A quick overview of this chapter:
- 3.2 Monitoring: What to measure throughout the tests and when to collect the data.
- 3.3 Test Scenario 1: A quick and a detailed description.
- 3.4 Test Scenario 2: A quick and a detailed description.
- 3.5 Testing Environment: What hardware and software is used.
- 3.6 Parameters: Presentation and explanation of all test parameters.
- 3.7 Development: Notes from the test scenario development.

3.2 Test Scenarios

This section gives a quick description of the two test scenarios and what components they consist of. A more detailed view of the information flow for each scenario, is found in section 3.6.

3.2.1 Test Scenario 1

Note: There are 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 different version. For individual 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 long-lived connection. The backend regularly sends messages to the server and it is 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. In a real world scenario, the clients would be web browsers.

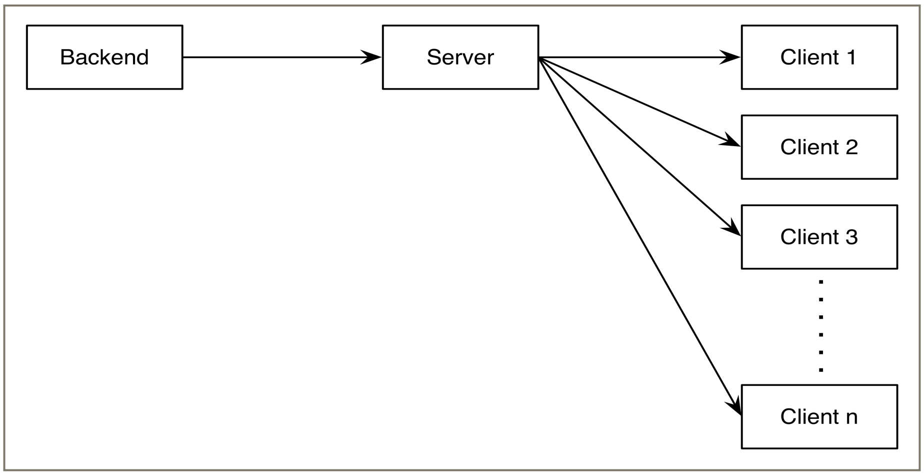


Figure 17: Simple diagram showing the three components. Messages from the backend are broadcasted to all clients.

3.2.2 Test Scenario 2

Note: There are three implementations of this test scenario, one with WebSocket alone, one with Server Sent Events (HTTP POST for client-to-server messages) and one with HTTP Long Polling (HTTP POST for client-to-server messages) and the text describing this scenario will not distinguish between the different version. For individual 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.

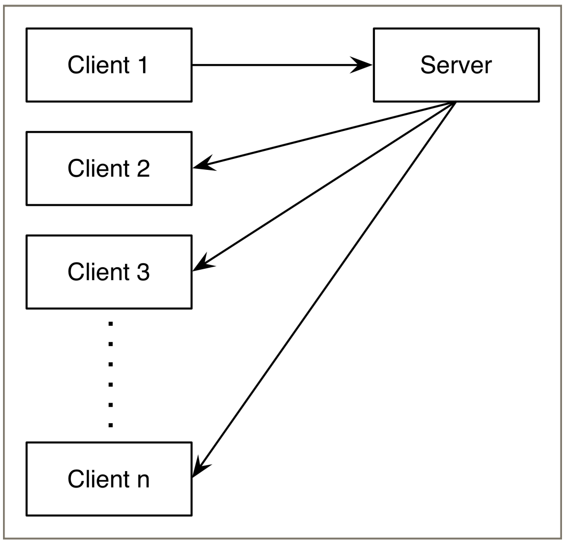


Figure 19: Simple diagram of the two components involved in the chat scenario. Client 1 sends a chat message to the server and the server broadcasts this to the other connected clients.

3.3 Test Data

The research questions state that the purpose 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 different transports. Stress testing the server is done by gradually increasing the number of connected clients, to the point where the server is utilizing the CPU at a maximum. As long as the CPU utilization is below maximum, the test is a Load test.

This section describes what data and used to compare the three different transports on a performance basis.

3.3.2 Two Points of View

There are two points of view with these tests. The first point view is the *server side*. From a server administrator's point of view, efficient use of server resources is important. The most interesting metrics from the server side is *CPU load* and *memory footprint*.

The other perspective is the user's. As a user of a real-time system, you do not care about how much stressed the server is under, as long as the system is responsive and quick to use. The only interesting measure from a user's point of view is the *response time*. How long it takes for the system to respond on an action.

To summarize, there are three metrics that are collected, the CPU and memory footprint on the server side, and the response time from the client's perspective.

3.3.3 Collection Through Three Test Phases

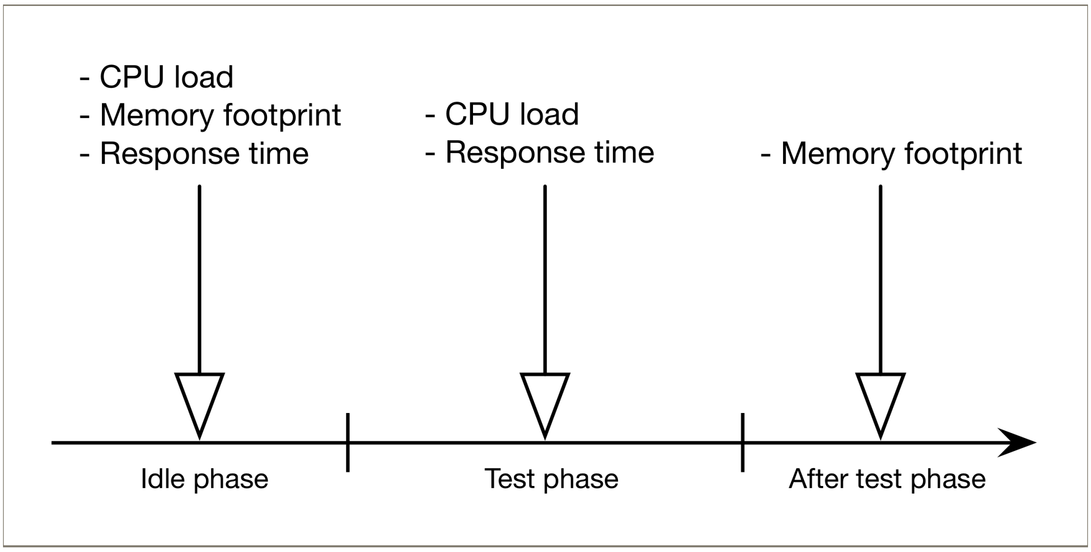


Figure 16: The three test phases and what is measured in each phase.

I have designed the tests to live through three phases. The first phase is the *idle phase*. The idle phase starts as soon as all clients are connected (or polling) to the server and everything is set for the test to start. In this phase, all three data metrics are collected.

The second phase is the *test phase*. During the test phase, the test is active and running. In the first test scenario, this is the phase when the server broadcasts messages received from the backend. In the second test scenario, this is the phase when the chat is live. The memory footprint will gradually increase throughout this phase as the server receives more messages. But, the garbage collector could clean and free memory space as well. Because of this uncertainty and unpredictability in terms of memory use, the memory footprint is not collected during this phase. CPU load and response time is collected.

The last phase is the phase immediately after the test have finished running. CPU and response time will be the same in this phase as in the idle phase, as the clients are inactive (or disconnected), but the memory consumption would be higher. As stated in the paragraph above, there are some uncertainties with regards to memory, but I decided to collect memory footprint after the test, to make sure I spot any (if present) irregularities.

3.3.4 Collection

The server side metrics (CPU load and memory footprint) are collected by a separate monitoring process running on the server machine. Every 50th millisecond the CPU load and memory footprint is recorded. The server process notifies the monitoring process when the different phases are started and it is the monitoring process' responsibility to calculating the CPU load and memory footprint average when the test is finished. This average is sent to the server for print out on the screen.

The client side metric, response time, is collected differently in the two test scenarios. In the first scenario, there is a separate ping client that every 50th millisecond sends a timestamped ping message to the server. The server immediately sends this message back and the ping client calculates the response time. In the second scenario, each chat message going to the server includes a timestamp, and each client is responsible for calculating and recording the response time of each message it receives. An average of those recordings is calculated once the test is over.

3.3.5 Number of Test Runs

To minimize any irregular results, each test is run 10 times for a given number of clients. An average of those ten tests is calculated at the end.

3.4 Testing environment

3.4.1 Hardware

When performance testing the server, it is important that it is isolated from all the other components. The server process must not be disturbed by some other part of the system, like the clients. 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 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 subsection 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.

3.4.2 Programming environment

The point of this thesis was to test and benchmark different transports - protocols. But, benchmarking protocols is not really possible as a protocol is just a set of rules. Implementations of protocols, on the other hand, is possible to benchmark.

To get the most accurate picture of how WebSocket compares to Server Sent Events and Long Polling, I would have to compare each and every single implementation of the transports to each other. But that would take a very long time and is not feasible for this thesis.

I could have chosen the most popular real-time frameworks and compared them, but that is essentially what Kristian Johannessen did.

As previously stated, Node.js is the chosen software platform. This subsection discusses why Node.js is a good match for this thesis.

Node.js is lightweight, very performant and easy to use

When PayPal moved from a Java backend to Node.js, they found incredible results[31]. After some tests they saw that the Node.js server could handle double the requests per second compared to the old Java server. They say this was "…interesting because our initial performance results were using a single core for the node.js application compared to five cores on Java…". They also saw a 35% decrease in average response time.

In addition to being very performant, their Node.js application was "Built almost twice as fast with fewer people". It was also written with 33% fewer lines of code and 40% fewer files compared to the old Java server.

It is also worth mentioning that JavaScript is an interpreted language. This can make development fast, especially with tools like nodemon[32].

Great performance and programmer friendliness makes Node.js great for the one man job this thesis is.

Node.js is single threaded

The fact that Node.js uses only one operating system 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.

PayPal said that their single threaded Node.js server performed better than a five threaded Java server. That makes Node.js great at scalability. Just start another instance of the server process!

Node.js is a platform with cutting edge innovation

When looking at GitHub's most trending and starred repositories[33], Node.js is the web framework that by far is most popular. It is also clear that most of the popular GitHub repositories are JavaScript projects. Since Node.js is a JavaScript runtime, most JavaScript code written for a web browser can also be used on the backend with Node.js.

Node.js comes with the great package manager NPM[34], that makes it really simple to quickly fetch new pieces of code and integrate them into your system.

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 is even a JavaScript interface to the OS[35]. Also, I chose it so that I can learn its quirks[36], 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 with the readline module[37]. This makes it perfect for the lightweight clients.

3.4.3 Command Line Clients

In his Further Work section, Kristian Johannessen[2] suggested using smaller lightweight console applications or headless browsers as clients. 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.

3.5 Test Configurations

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.

3.5.1 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.

3.5.2 Parameters Specific to the First 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

Given that I could only have a maximum of 500 client processes, the clients had to quite rapidly send new messages, in order to stress the server well before reaching 500. Every *5th* milliseconds a new message is sent from each client.

The Size of Each Broadcast 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[38]. 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

To make the test run long enough to minimize inaccuracies in CPU use caused by the garbage collector, but at the same time make it feasible for the time I had at hand, I set this number to 5000. With 5 milliseconds between each message, this means that each test run for 25 seconds.

3.5.3 Parameters Specific to the Second 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 Chat 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 two messages.

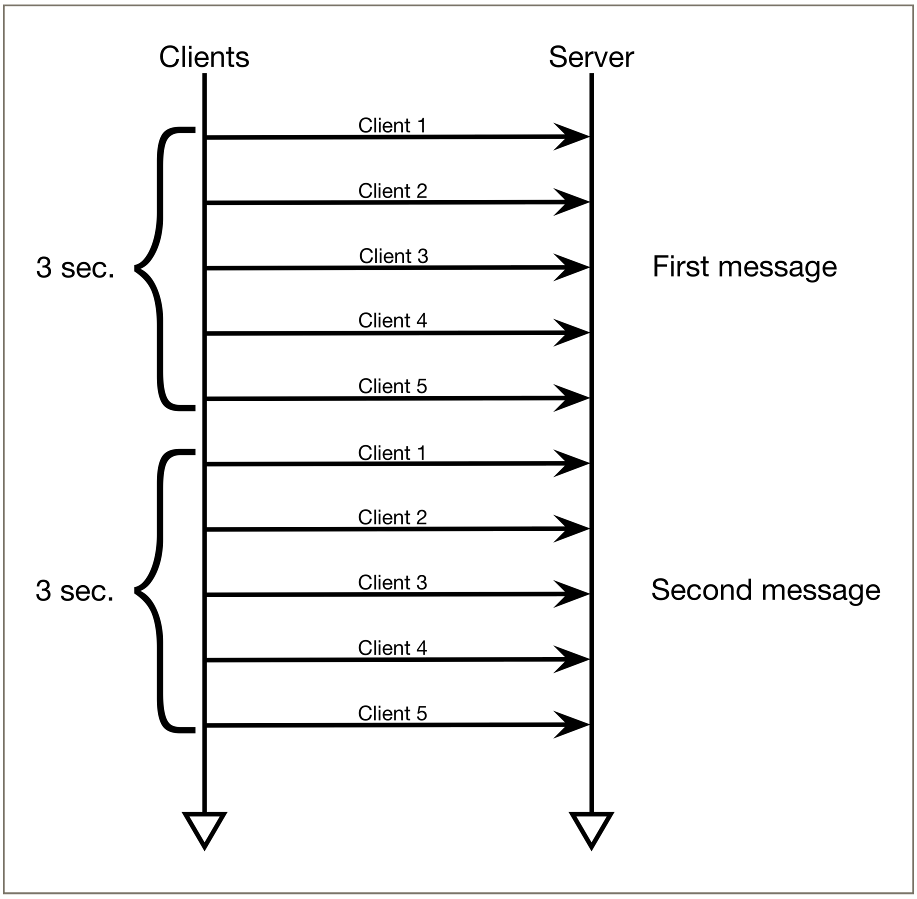


Figure 21: Example showing five clients sending their first two messages.

3.6 Detailed Information Flow

3.6.1 Test Scenario 1

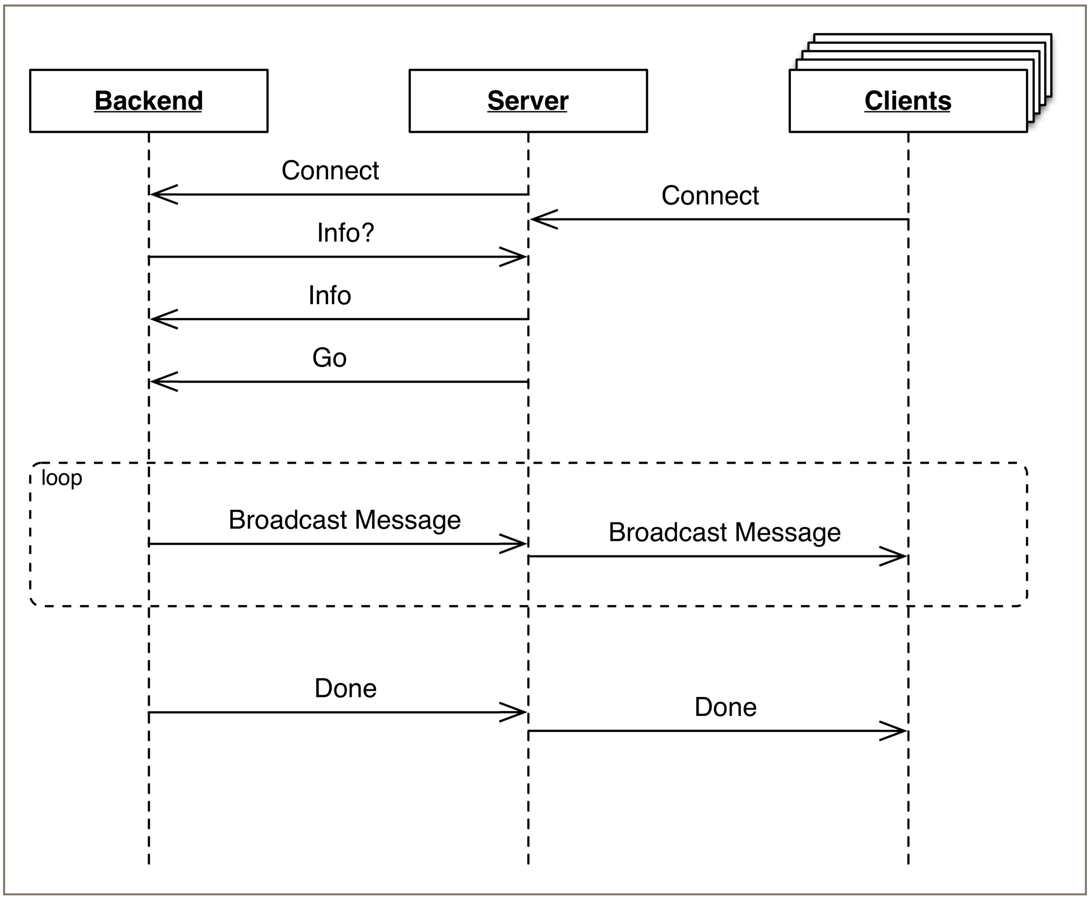


Figure 18: Sequence diagram showing detailed information flow. For simplicity the master client is not included.

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. It is up to the user on the server to make sure all clients are connected before sending the go message to the backend. The go message is sent once the server registers a press of the return key.

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.

3.6.2 Test Scenario 2

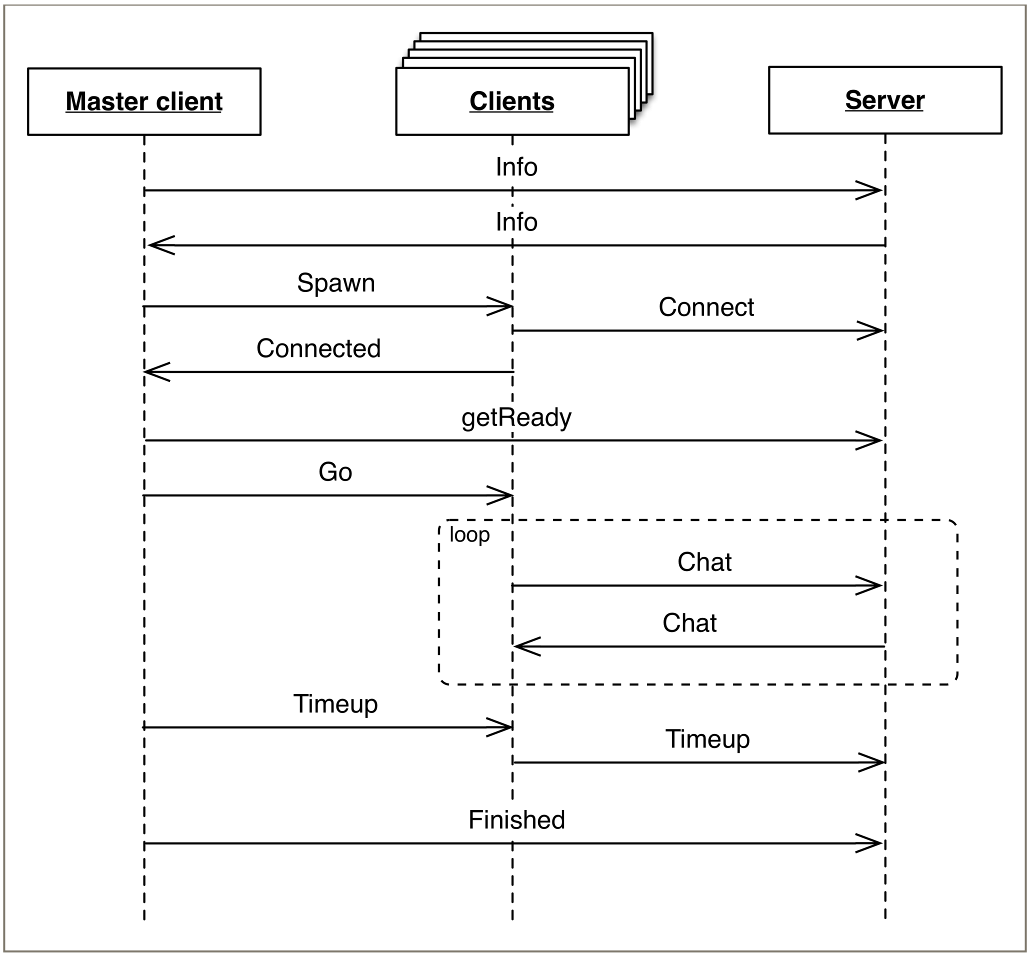


Figure 20: Sequence diagram showing the major flows of information for the chat test.

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 process spawning takes place, the master client exchanges information with the server. This exchange makes sure that both parties how many clients are involved and for how long the test should run.

Each spawned client is given the server address and immediately connects to the server. The child process 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 and tell all clients when to start chatting with a *go* message. The timer is there to stop the chat after the desired time.

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

Once the test timeout runs out and the test is over, each client sends 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.

3.7 Development

3.7.1 Regarding Libraries

The point of this thesis was to test and benchmark different transports - protocols. But, benchmarking protocols is not really possible as a protocol is just a set of rules. Implementations of protocols, on the other hand, is possible to benchmark.

To get the most accurate picture of how WebSocket compares to Server Sent Events and Long Polling, I would have to compare each and every single implementation of the transports to each other. But that would take a very long time and is not feasible for this thesis. I could have chosen the most popular real-time frameworks and compared them, but that is essentially what Kristian Johannessen did.

Recommended by Kristian Johannessen, I chose to focus on a single platform, with as bare-bones implementations as possible.

as there are several implementations of different protocols. Microsoft Internet Explorer has its implementation of WebSocket and Google Chrome has its, as an example. Testing certain implementations are, on the other hand, possible. It was clear from the start that I did not want the thesis to be about comparing different libraries or frameworks, Kristian Johannessen[2] 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[39]. 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[40] 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[41] WebSocket implementations, regardless of platform, 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[42]. 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[43]* helped to make that a simple reality. In addition, the small library *request[44]*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[45] was used. It provides a simple interface to get CPU and memory usage of a process, using the UNIX application ps.

3.7.2 Software Versions

To see what version of Node.js, 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 Test Configuration 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.

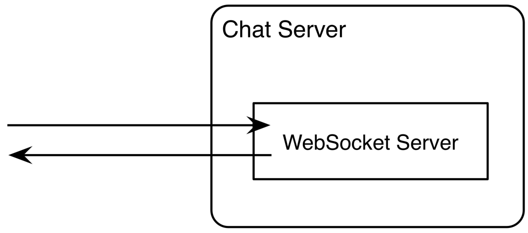


Figure 23: The WebSocket chat server

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.

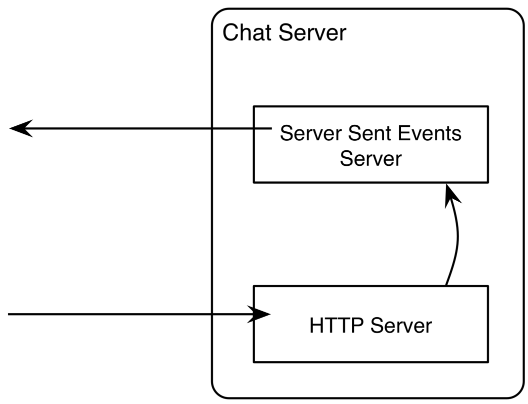


Figure 24: The Server Sent Events chat server with HTTP POST for incoming messages

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.

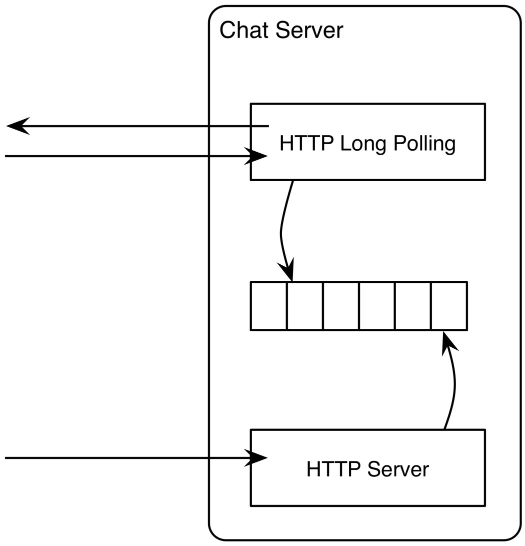


Figure 25: The HTTP Long Polling chat server with local array as message store and HTTP POST for incoming messages

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

Because of time constraints and the choices I have made to finish this thesis in time, there are some limitations to the methodology described in this chapter. This section looks into them one by one.

3.8.1 Performance Over Longer Periods of Time

How the different transports 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 unsuitable for this master's thesis.

3.8.2 Network Use

In the background chapter, difference in packet size between WebSocket and HTTP was pointed out. Potentially we could see a significant difference in network use between the three transports. However, for simplicity's sake the tests was designed so that the network would not be a bottleneck. That makes it easier to find the break point between a load test and a stress test, as network factors can be ruled out.

3.8.3 Quality and Correctness of the Code

There is always a chance that the test code is not written in a satisfactory manner. 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 used by thousands, bugs and errors can occur[46]. I do not believe my tests are written in an incorrect or error prone way. The reason I believe this is that the test results from the first scenario are comparable, and similar in some ways, to the results from the second scenario (as seen in the following two chapters).

3.8.4 Only One Software Platform

The fact that I have chosen to do the performance testing on a single software platform introduces a couple limitations to the methodology.

First, the picture I get of WebSocket, Server Sent Events and Long Polling is a reflection of how these transports perform on the Node.js platform, not in general. However, since a thesis is time constrained and with recommendation by Johannessen[2] in his thesis's Further Work section, performing the tests on a single platform is a good choice.

The other limitation is that relying on a single platform for the tests, makes it vulnerable to errors or bugs in the chosen platform. A bug or fault in Node.js would to a certain degree compromise the results.

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[2], 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.

3.8.5 Node.js

As discussed previous in this chapter, Node.js is a good fit for the tests in this thesis. However, there are some aspects of Node.js one needs to be aware of.

First, the V8 JavaScript engine powering Node.js employs a garbage collector. This means that memory allocation and deallocation is handled by the runtime. V8 uses the stop-the-world collection scheme[47]. This means that V8 stops all program execution once the garbage collector runs. Because of this, response time may occasionally increase when the garbage collector does its work. CPU load may also be affected by the garbage collection.

The Event Loop is another part of Node.js that needs to be understood. I briefly presented the Event Loop in the background chapter, but did not mention the following weakness. When the Event Loop has triggered and called a callback, it is blocked. Usually not for long, but if it is stuck on a very computational task, it can cause slow response times or connect issues[48]. This could lead to issues in my tests, with the broadcast function that is called when a broadcast message (scenario 1) or a chat message (scenario 2) is received.

4 Results

4.1 Introduction

This chapter presents the results from the two test scenarios. Each of the two tests were run ten times for a given number of clients. The client count goes from 1 to 500 with increments of 50. This means a total of 110 test runs (10 test runs * 11 different client counts) for each of the two test scenarios. The average of each of those ten test runs is calculated. It is this average that is used to draw the charts in this chapter. For the complete test result records, see the Appendix.

Result discussion or analysis is absent in this chapter, as that is reserved for the Discussion chapter. This chapter is meant to be a objective representation of the results.

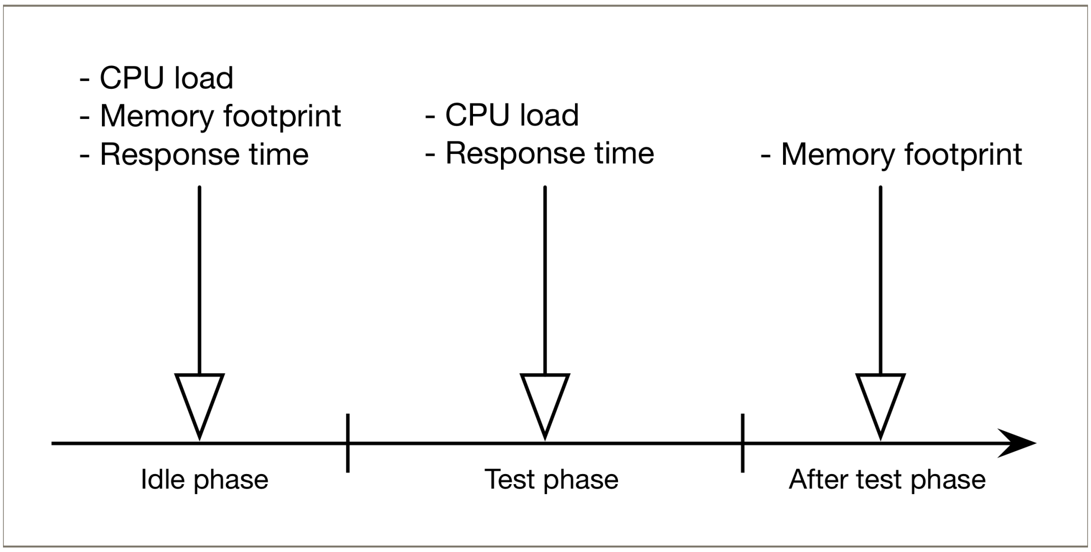


Figure 26: The three test phases and what is measured in each phase.

As previously stated there are built around three different phases. These phases are illustrated by the figure above. The results are presented using the same division:

1. Idle phase: CPU load, memory footprint and response time in the
2. Test phase: CPU load and response time.
3. After test phase: Memory footprint

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. Idle clients should consume as little server resources as possible enabling a short response time for clients.

It does not matter whether the server is a simple broadcast or a chat server in the idle phase as the connected or polling clients are inactive. This means that the first phase is common for both test scenarios.

4.2.1 CPU Load

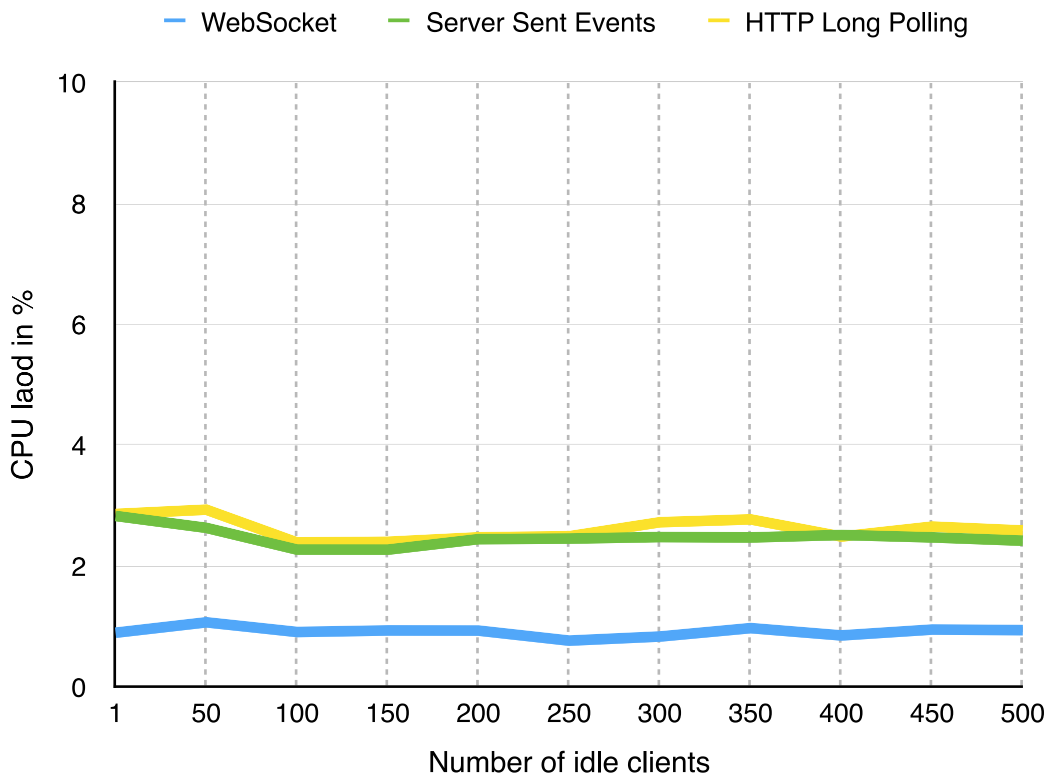


Figure 26: The CPU load for all three transports during the idle phase.

All three servers used so few CPU cycles that the Y scale had to be set to a maximum of 10% to to show the difference between them. The Long Polling and Server Sent Events servers perform very similar, almost identical, with a CPU load between 2 % and 3 %. The WebSocket server uses even less CPU cycles and stays around just 1 %.

It is also worth mentioning that the increase in client count does not affect the results. Even though the client count reaches 500, the CPU usage stays as low as with 1.

4.2.2 Memory Footprint

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

The HTTP Long Polling and Server Sent Events servers both start off just shy of 30 MB. Their memory footprint then slowly rises as the client count increases. The Server Sent Events version consumes more memory per client compared to the Long Polling variant, but not by much.

The WebSocket server starts off at a very small footprint of 17 MB, but sees a larger growth as the client count increases. When the client count is 500, it has overtaken the Long Polling versions and just barely trails the Server Sent Events counterpart.

4.2.3 Response Time

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

The chart above shows the response time for the three different servers. Once again, we see that the Long Polling and Server Sent Events servers perform very similarly. They respond after 3 to 4 milliseconds. The WebSocket counterpart is significantly faster to answer the ping messages, never breaching the 2 millisecond mark.

Once again, increasing the number of clients have no effect on the results. The response time stays low even with 500 clients.

4.3 Test Phase - Scenario 1

The results in this section are from the first scenario. They are collected from right after the broadcast phase is live to just before it ends. This way abnormalities from the initialization and tear down are eliminated.

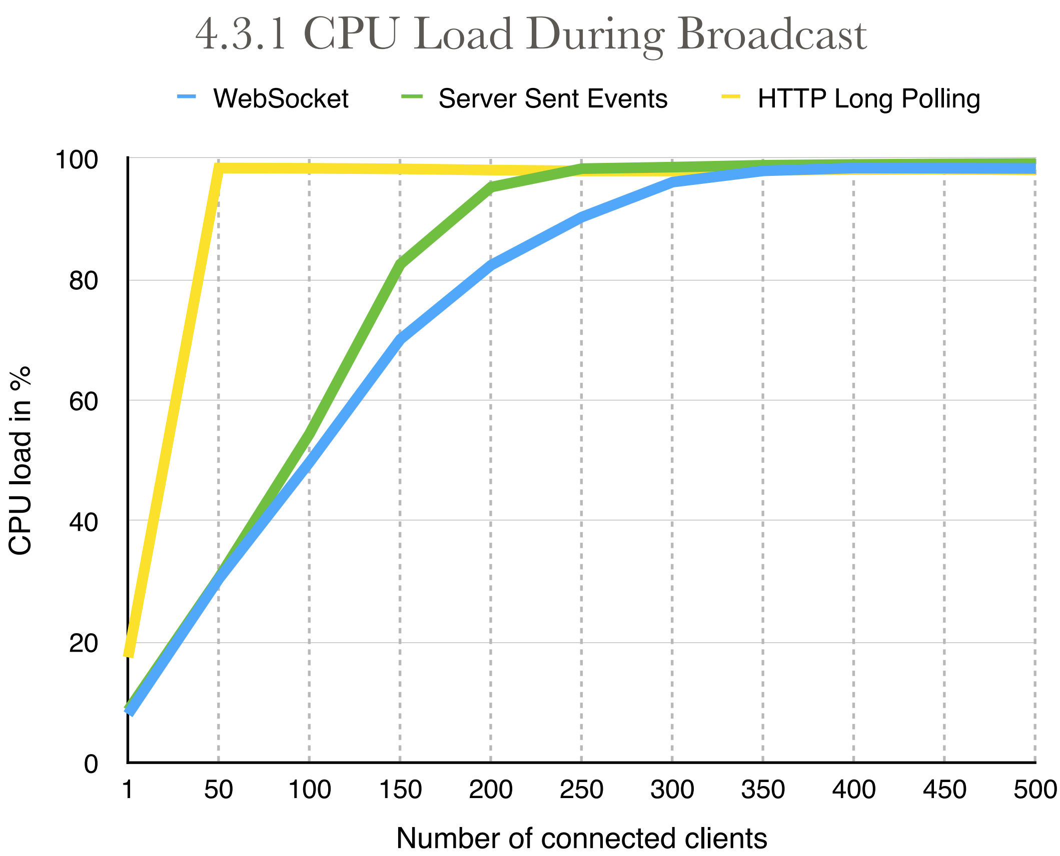


Figure 29: The CPU load during the first test scenario's test phase

The HTTP Long Polling server starts off at 17 % CPU load for one single client. This puts it well ahead of the other two servers that starts off at 8 %. Then the Long Polling server skyrockets to full CPU utilization with only 50 polling clients. The Server Sent Events and WebSocket servers have a more relaxed increase in CPU use, reaching full CPU utilization at 250 and 350 clients respectively.

4.3.2 Response Time During Broadcast

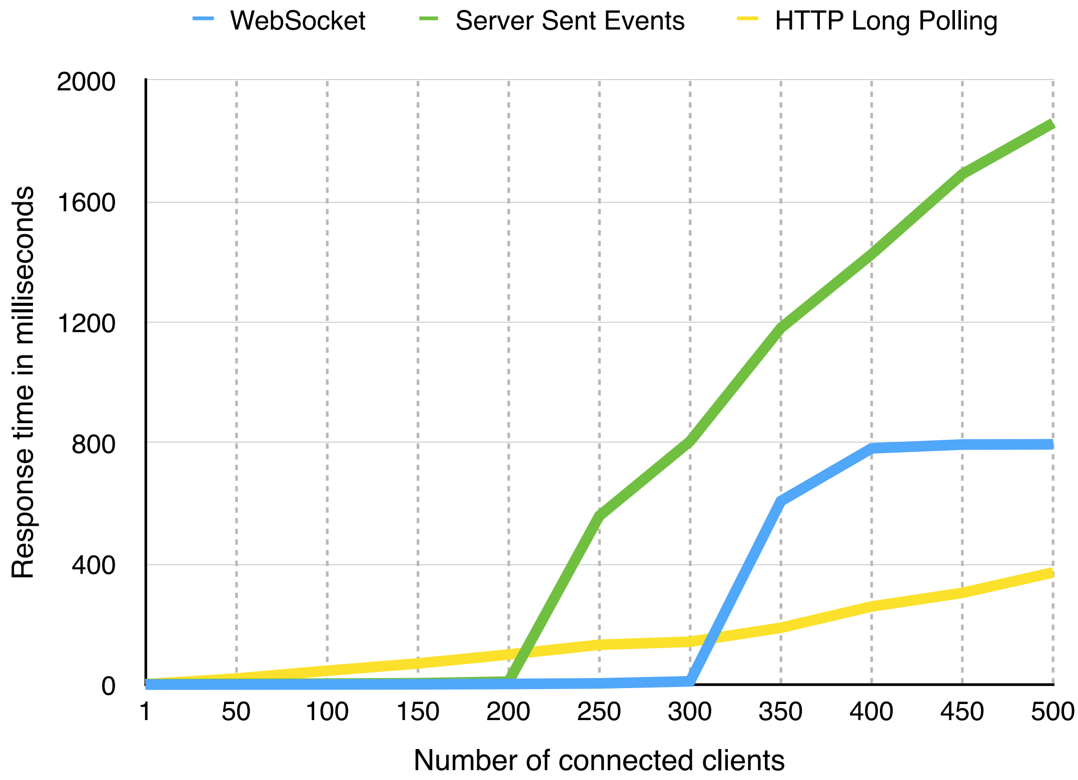


Figure 30: The response times during the first test scenario's test phase

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.

Even though the sudden spikes in response time seem unnatural and anomaly like, they were encountered in all 10 test runs. Chapter 5 takes a deeper look into why this happens.

4.4 Test Phase - Scenario 2

When the second test scenario was 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. However, when all test results were collected, the median was not to far off from the average. Consequently I will only present the average. The response time median can be found in the Appendix.

As with the first scenario, the results here are collected from right after the chat phase is live to just before it ends.

4.4.1 CPU Load During Chat

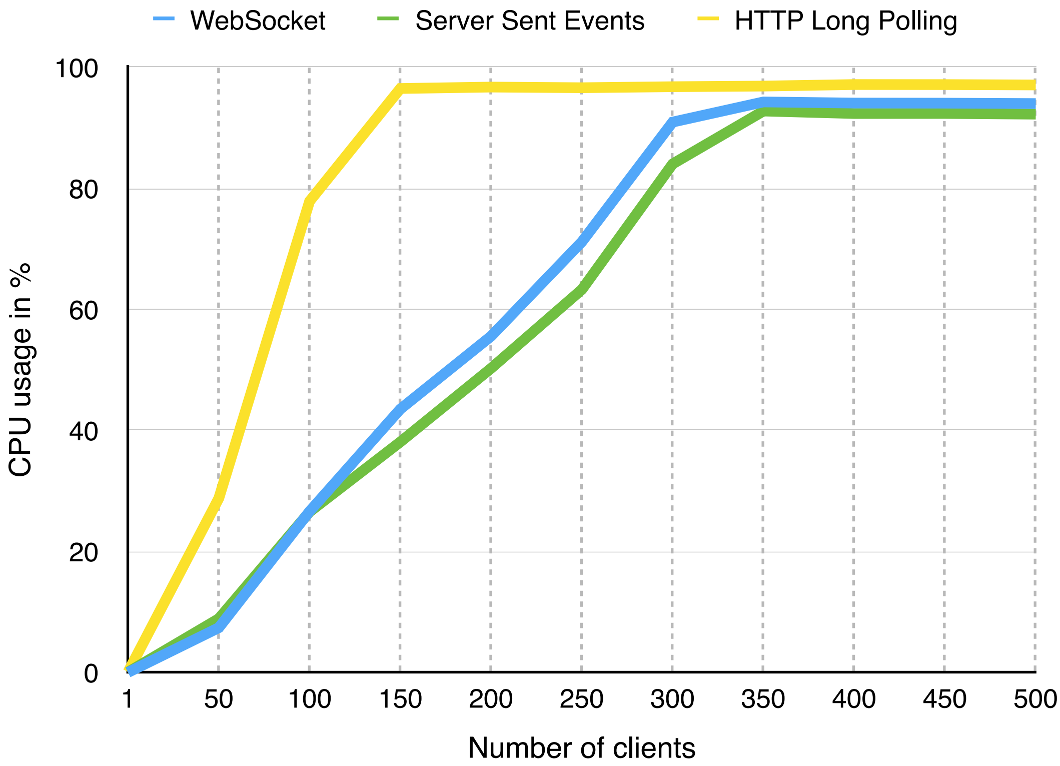


Figure 31: The CPU load during the seconds test scenario's test phase

Not too different from the first scenario, we see that the HTTP Long Polling server immediately requires a lot more CPU power than the other servers. It reaches its maximum CPU utilization with 150 clients, while the other two servers reach peak CPU usage at 350 clients.

This time around, WebSocket and Server Sent Events are very similar, with the latter being the most efficient.

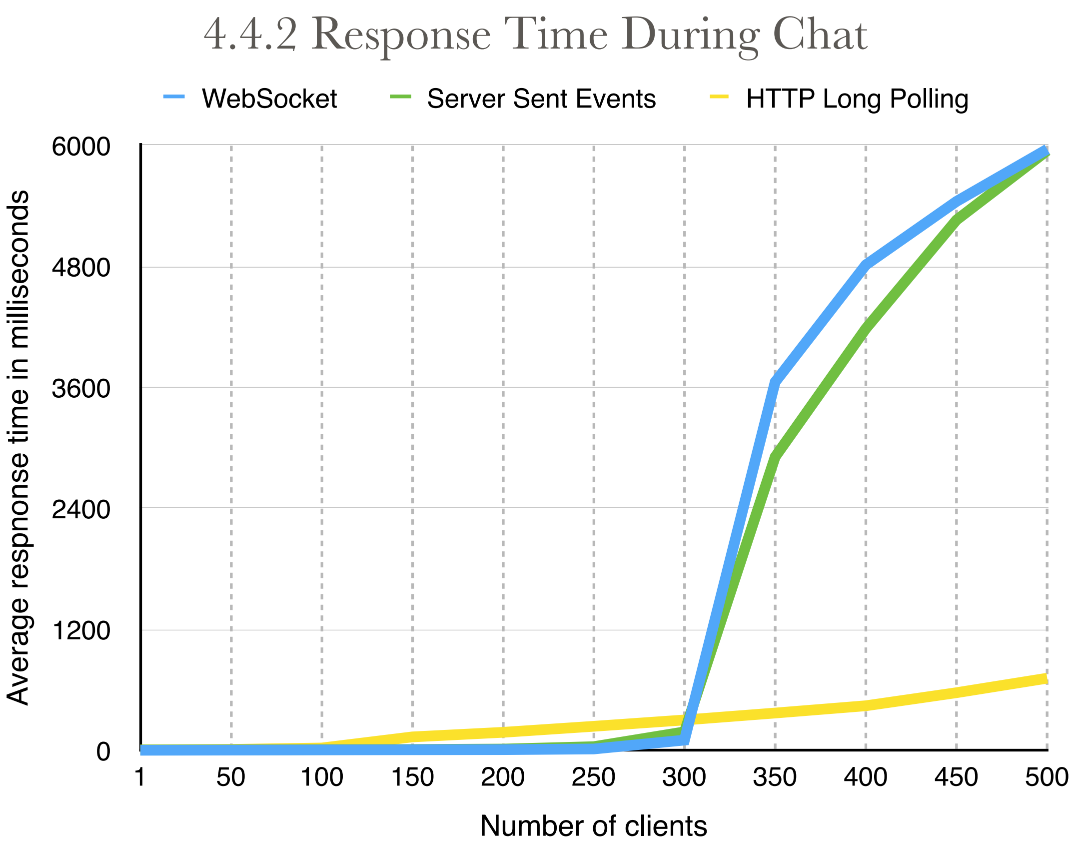


Figure 32: The response times during the second test scenario's test phase

When the Long Polling server reaches full CPU load at 150 clients we see a small jump in response time. From that point the response time increases steadily and linearly as the client count rises. With 500 polling clients, the Long Polling server responds to ping messages within 0,7 seconds.

The WebSocket and Server Sent Events servers are very similar here. They both start off with a very quick response time and it stays low as the CPU is not stressed. At 350 clients, when the CPU load reaches maximum, the response time very dramatically escalates. When there are 500 connected chat clients, the servers uses almost 6 seconds to respond.

4.5 Memory Footprint After Tests

4.5.1 Test Scenario 1

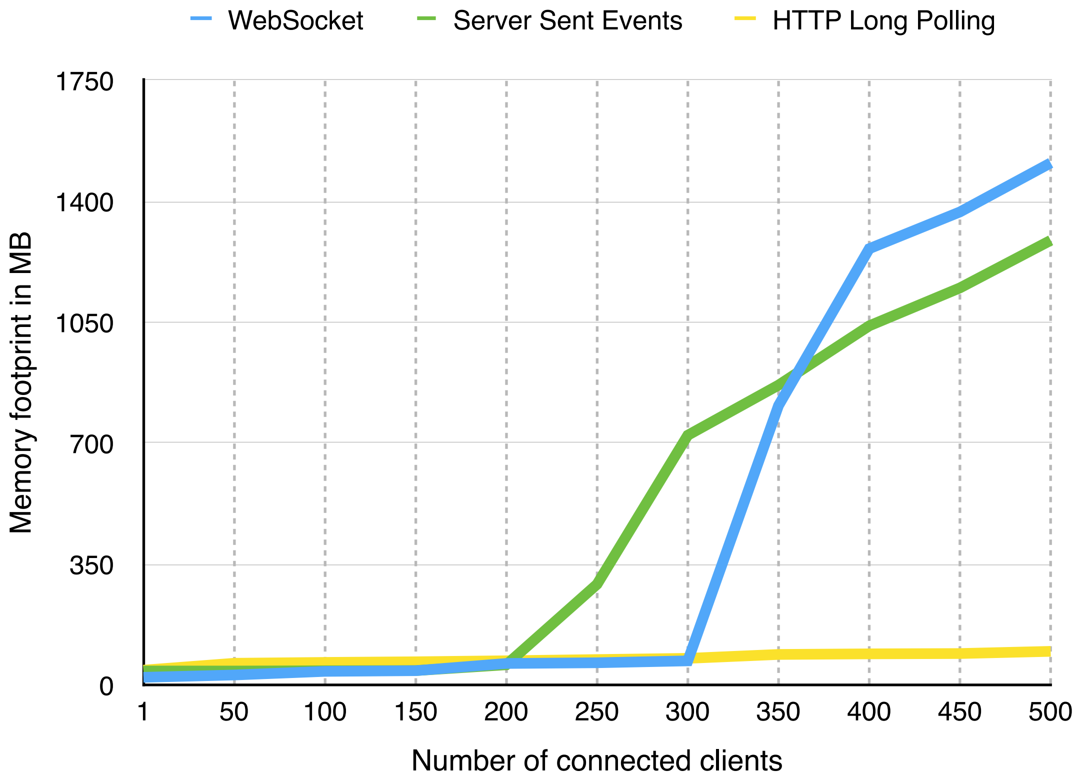


Figure 33: The memory footprint right after the first test scenario's test phase

The HTTP Long Polling server has a small and steady increase in memory consumption after the broadcast is finished. It increases linearly with the client number. That is also true for the other two servers, but only initially. Just as with the response time, the memory footprint after the tests, increases dramatically when the CPU load peaks. After the 500 client test runs, the WebSocket and Server Sent Events servers consume more than 1 GB of memory.

4.5.2 Test Scenario 2

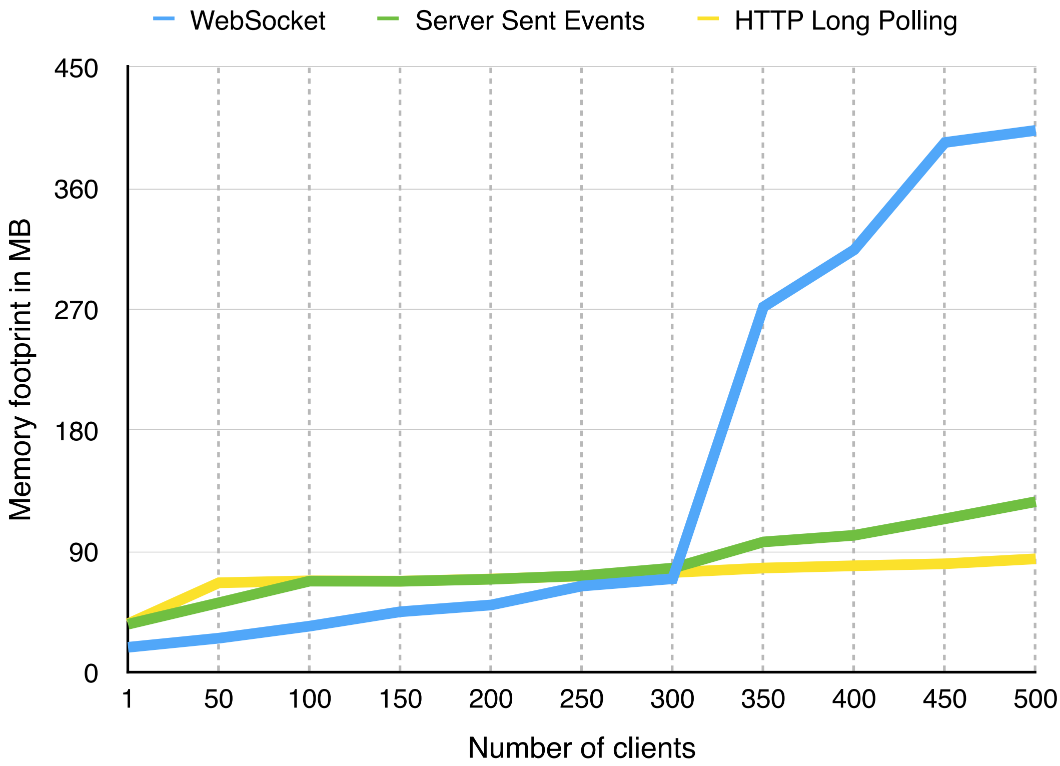


Figure 33: The memory footprint right after the second test scenario's test phase

Once again, the HTTP Long Polling server performs predictable and there is only a small an gradual increase in memory consumption. On the other hand, the Server Sent Events and WebSocket counterparts see a jump in memory footprint as they reach full CPU utilization at the 350 client mark. The jump is more significant for the WebSocket server, but definitely exists for the Server Sent Events server as well.

5 Discussion

5.1 Introduction

The Results chapter showed that the Server Sent Events and WebSocket servers experience explosive growth in response time and memory consumption when the CPU is stressed. Because of this, I have chosen to divide the discussion into the following 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[49] 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[43] 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[40] 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.

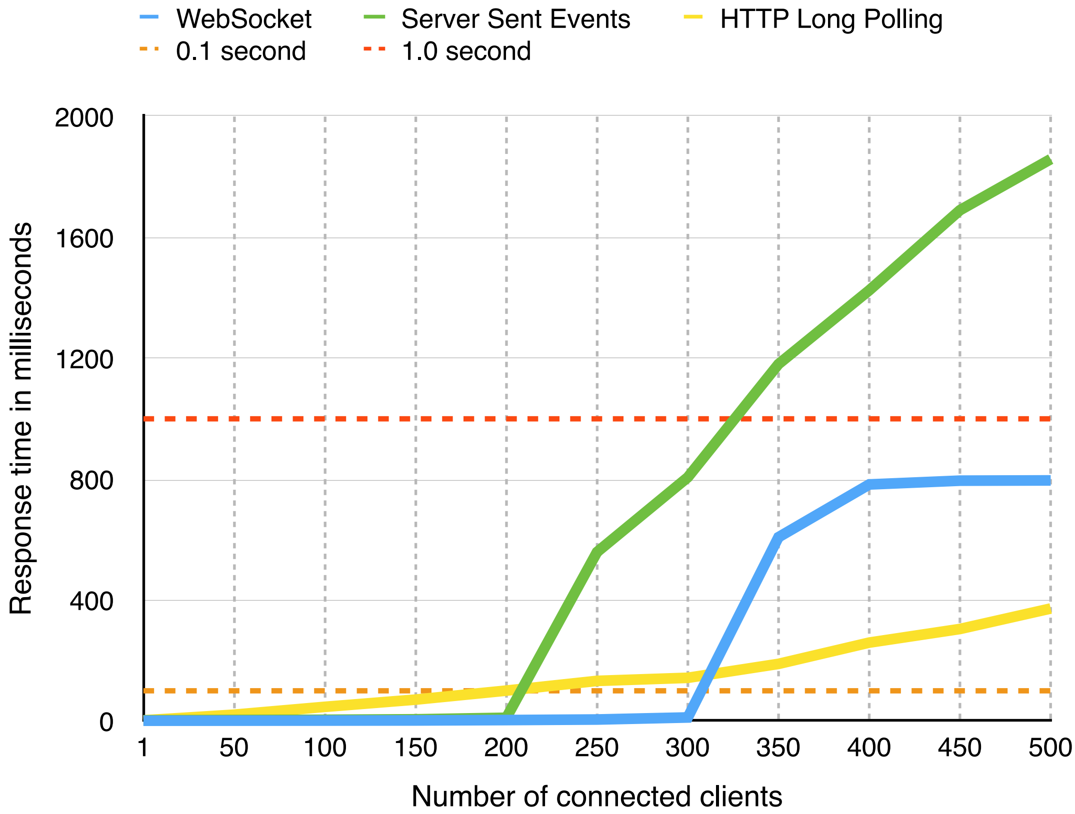


Figure 34: The response times during the first test scenario's test phase

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.

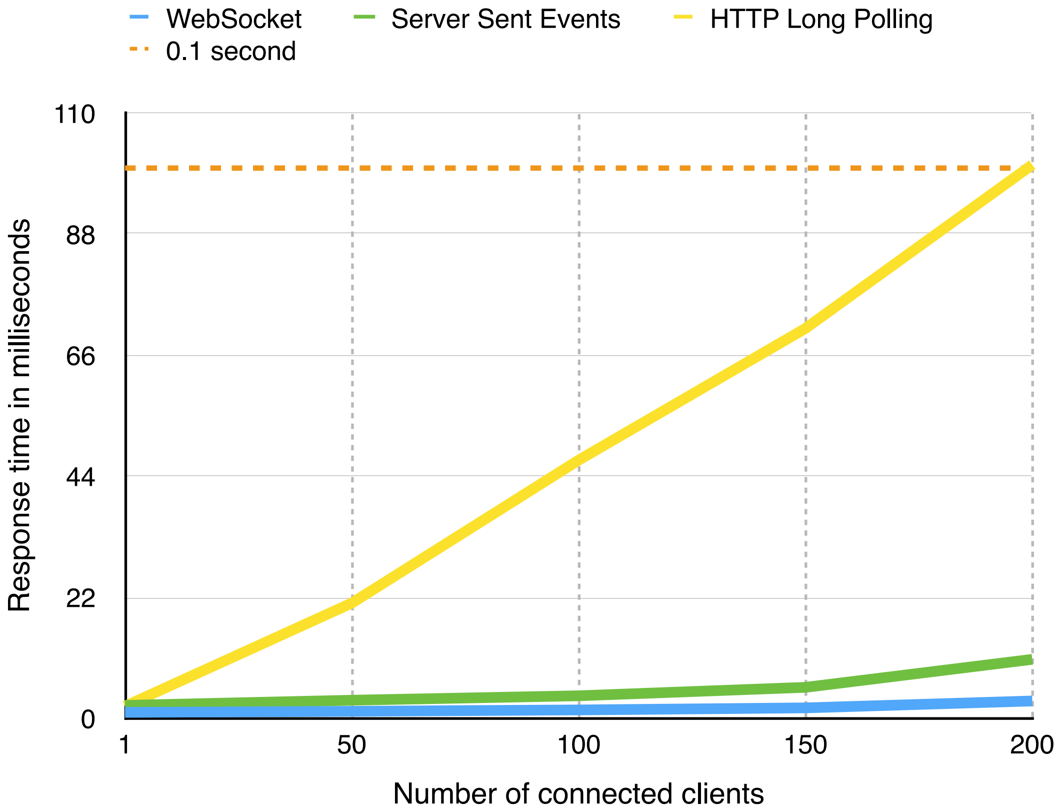


Figure 35: The response times during the first test scenario's test phase

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[2] 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.

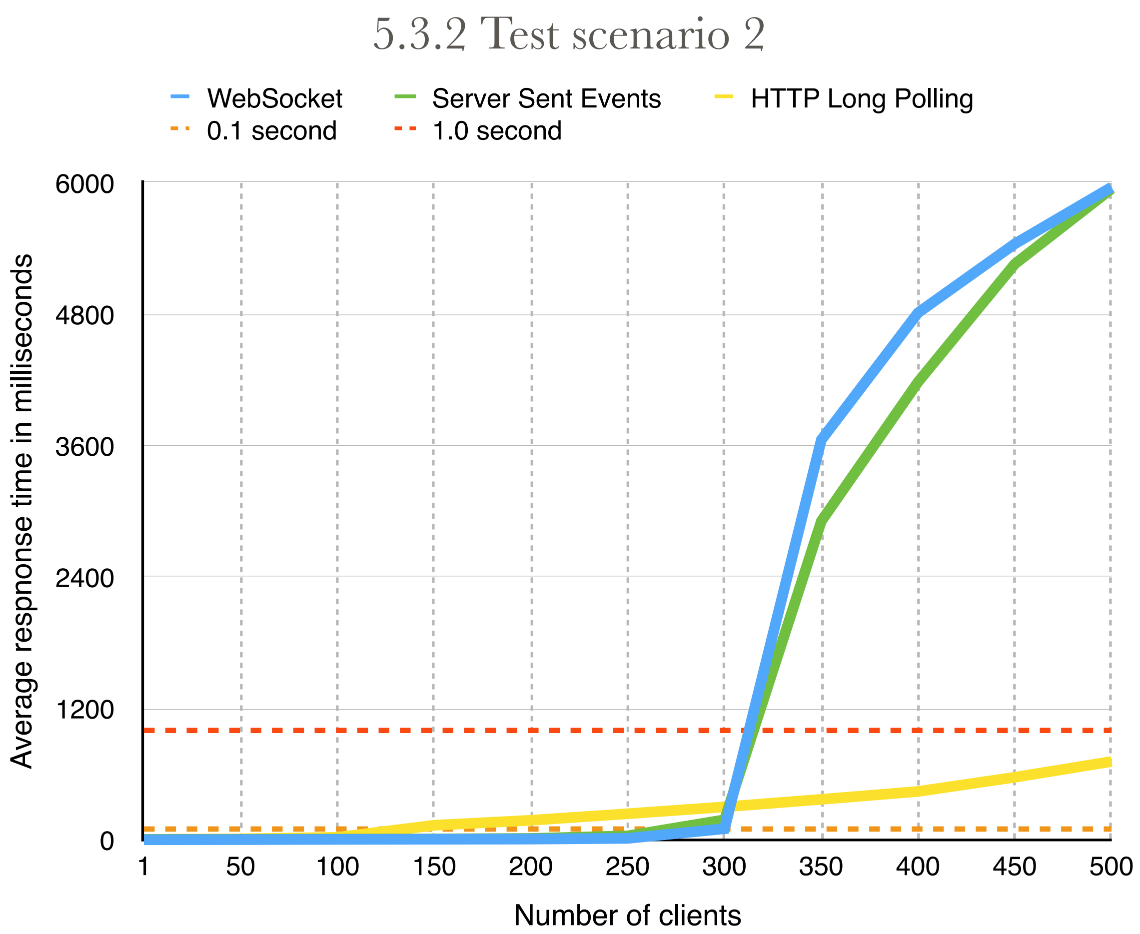


Figure 36: The response times during the second test scenario's test phase

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.

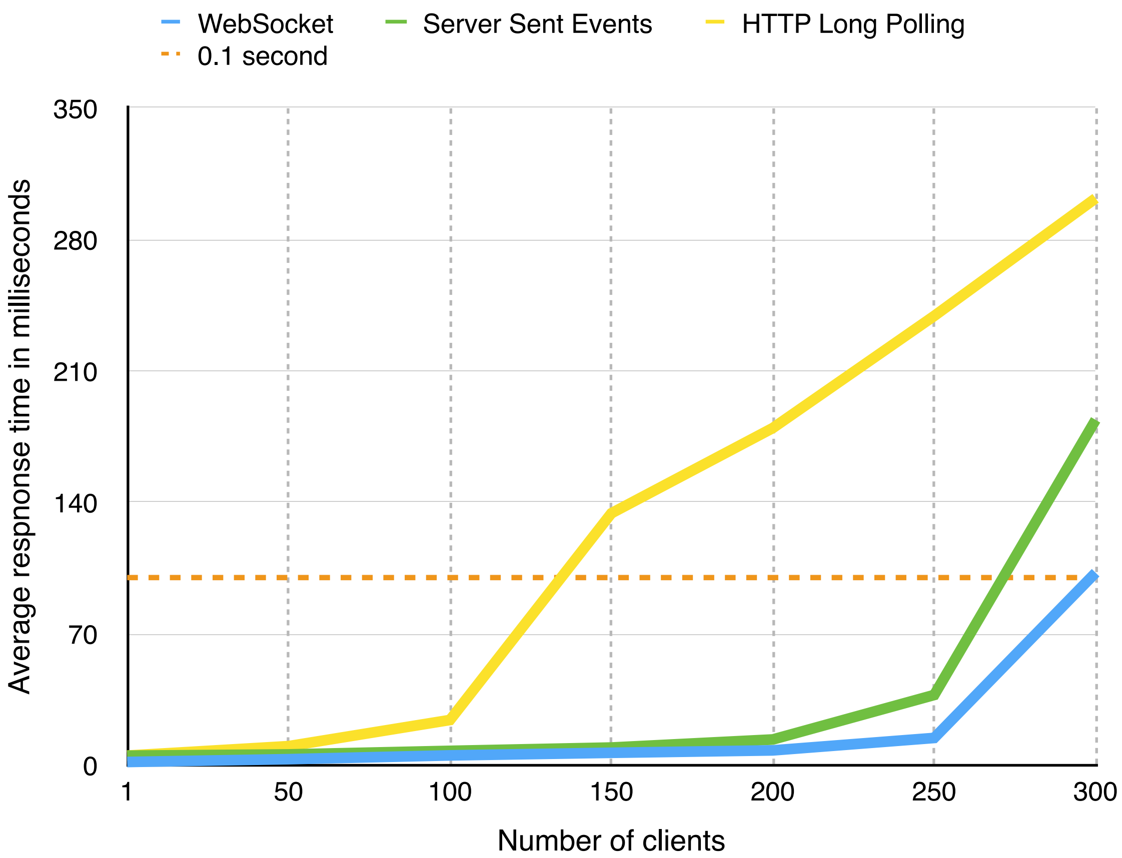


Figure 37: The response times during the second test scenario's test phase

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

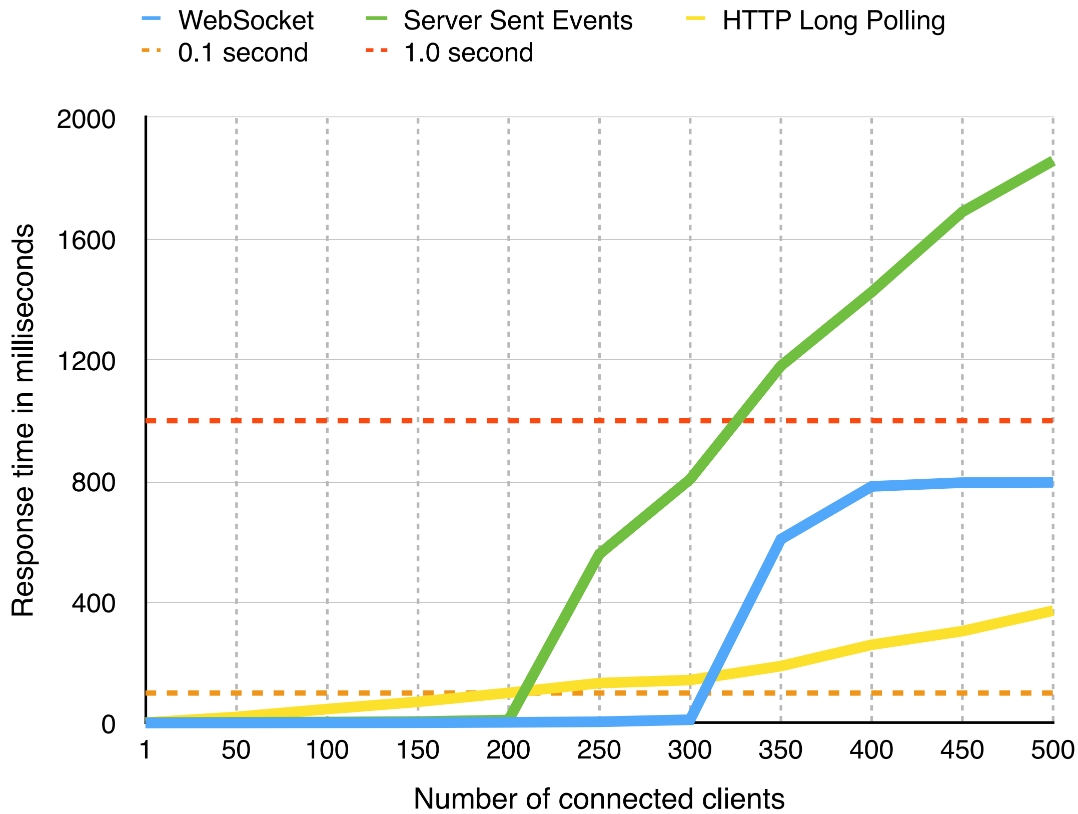


Figure 38: Response times during the broadcast phase in test scenario 1

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.

5.4.2 Test Scenario 2

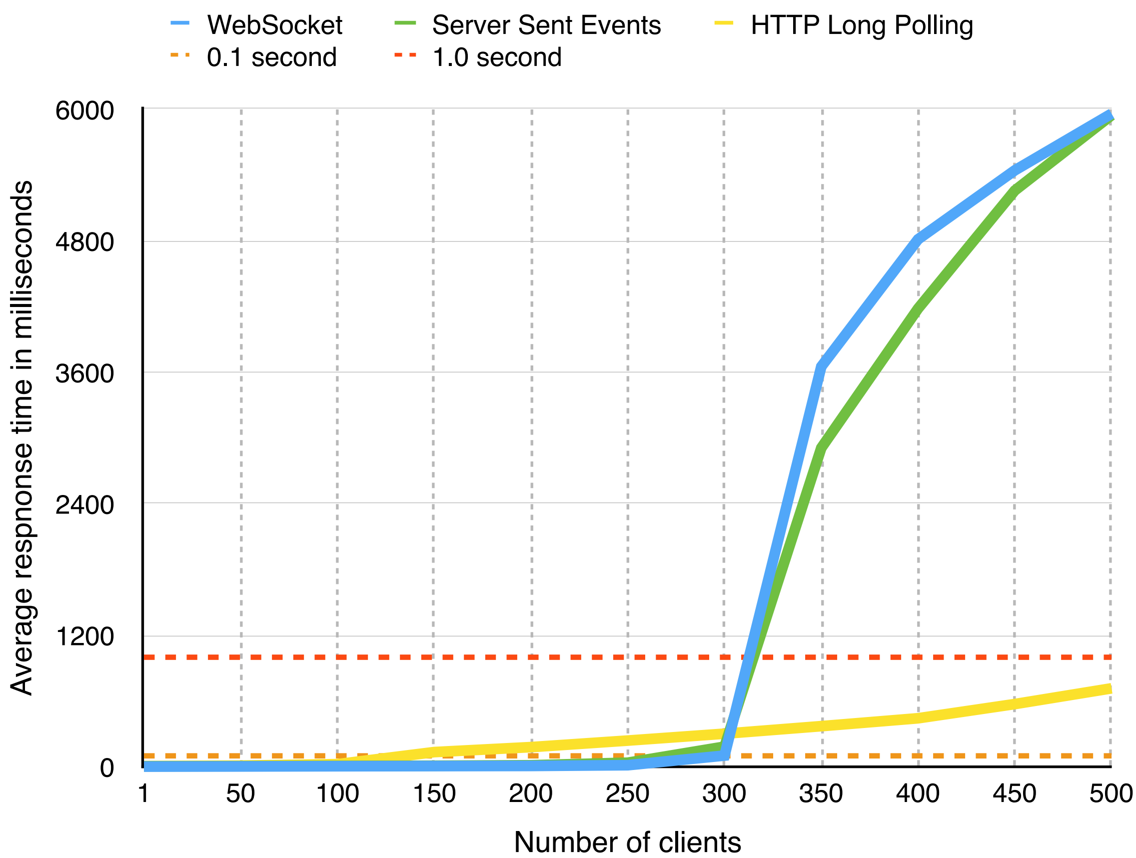


Figure 39: Response times during the chat phase in test scenario 2

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.

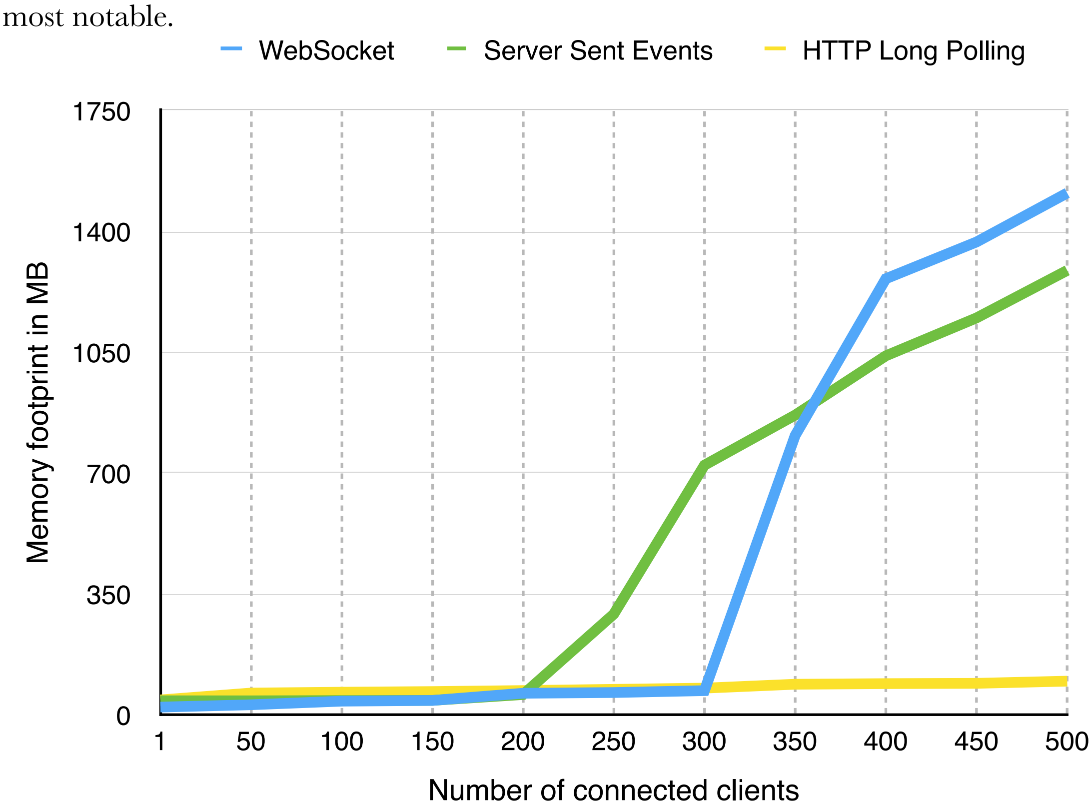


Figure 40: Memory footprint right after the broadcast phase in test scenario 1

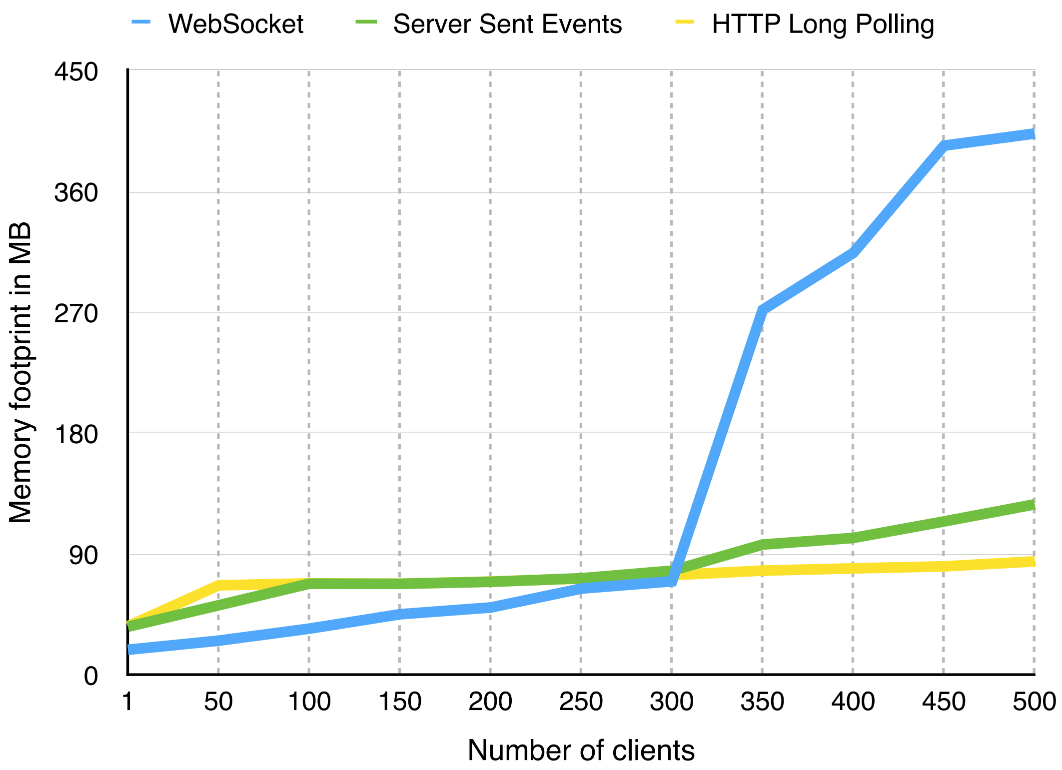


Figure 41: Memory footprint right after the chat phase in test scenario 2

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*"[50]. Memory leaks can cause the garbage collector to become more aggressive[51], 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[52] 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.

5.6 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

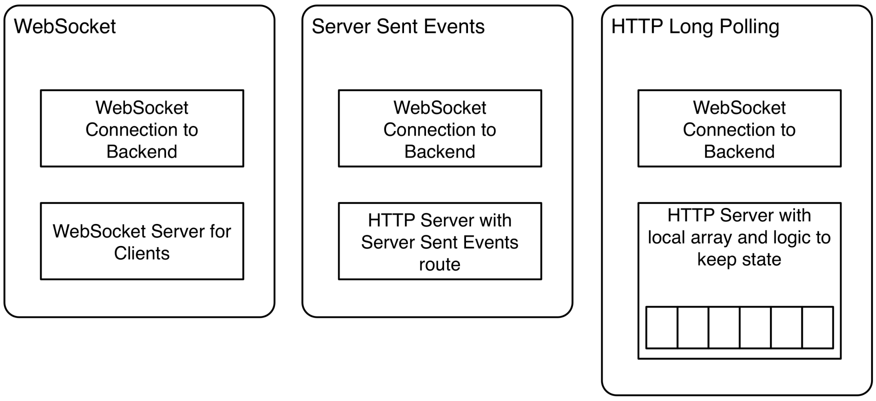


Figure 42: The three different servers in the first test scenario

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

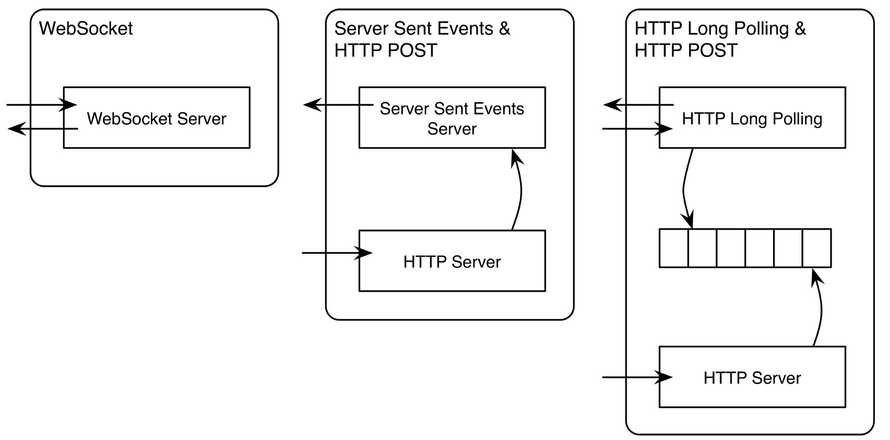


Figure 43: The three difference servers in the second test scenario including arrows for incoming and outgoing messages.

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.

5.7 Thesis Conclusion

Her svarer jeg direkte på problemstillingene. 1 side er nok.

5.8 Further Work

HTTP 2.0
WebRTC
Samme oppgave på flere software platformer

1 til 2 sider.

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Appendix

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

Code

Link to github

Software Versions

Link to github

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
```

Test Results

Idle CPU Load

HTTP Long Polling - Idle CPU Load

# clients	1	50	100	150	200	250	300	350	400	450	500
Run 1	3,00	2,42	2,29	2,30	2,54	2,44	2,70	2,78	2,36	2,67	2,54
Run 2	2,77	3,00	2,38	2,35	2,32	2,31	2,76	2,73	2,73	2,57	2,57
Run 3	2,81	2,97	2,41	2,42	2,41	2,38	2,64	2,93	2,43	2,62	2,77
Run 4	2,75	3,00	2,44	2,36	2,65	2,48	2,66	2,82	2,49	2,66	2,44
Run 5	2,80	3,18	2,38	2,43	2,34	2,48	2,81	2,73	2,45	2,55	2,75
Run 6	2,96	2,86	2,34	2,33	2,50	2,56	2,68	2,79	2,54	2,71	2,58
Run 7	3,05	3,00	2,44	2,30	2,55	2,57	2,60	2,50	2,54	3,00	2,49
Run 8	3,02	2,86	2,32	2,55	2,58	2,52	2,88	2,55	2,59	2,67	2,57
Run 9	2,47	3,14	2,47	2,33	2,40	2,65	2,84	3,02	2,41	2,47	2,66
Run 10	2,98	2,89	2,42	2,63	2,45	2,53	2,67	2,86	2,33	2,60	2,50
Average	**2,861**	**2,932**	**2,389**	**2,4**	**2,474**	**2,492**	**2,724**	**2,771**	**2,487**	**2,652**	**2,587**

Tekst

Server Sent Events - Idle CPU Load

# clients	1	50	100	150	200	250	300	350	400	450	500
Run 1	2,71	2,88	2,37	2,39	2,35	2,40	2,32	2,52	2,79	2,52	2,44
Run 2	2,44	2,67	2,29	2,41	2,70	2,47	2,31	2,40	2,29	2,31	2,49
Run 3	2,94	2,65	2,21	2,19	2,58	2,78	2,47	2,55	2,29	2,45	2,33
Run 4	2,83	2,63	2,27	2,21	2,32	2,49	2,64	2,45	2,40	2,21	2,54
Run 5	2,93	2,49	2,26	2,26	2,56	2,44	2,53	2,53	2,72	2,42	2,32
Run 6	2,86	2,51	2,23	2,25	2,61	2,37	2,71	2,45	2,37	2,63	2,32
Run 7	3,07	2,64	2,22	2,28	2,37	2,23	2,47	2,33	2,59	2,79	2,42
Run 8	2,77	2,50	2,24	2,29	2,29	2,36	2,53	2,67	2,47	2,46	2,54
Run 9	2,80	2,66	2,25	2,24	2,25	2,49	2,62	2,40	2,74	2,54	2,34
Run 10	2,93	2,68	2,37	2,18	2,41	2,50	2,19	2,42	2,47	2,40	2,44
Average	**2,828**	**2,631**	**2,271**	**2,27**	**2,444**	**2,453**	**2,479**	**2,472**	**2,513**	**2,473**	**2,418**

Tekst

WebSocket - Idle CPU Load

# clients	1	50	100	150	200	250	300	350	400	450	500
Run 1	0,98	0,65	0,48	1,04	0,91	0,83	1,02	0,97	0,89	0,72	0,93
Run 2	1,09	1,07	1,02	0,70	1,00	0,79	0,61	1,05	0,64	1,17	0,61
Run 3	1,05	1,21	0,93	0,86	1,06	0,90	1,02	0,54	1,05	1,11	1,05
Run 4	0,59	1,05	0,67	0,71	1,03	0,53	1,02	0,61	0,89	0,98	1,32
Run 5	0,62	1,02	1,09	1,15	0,93	0,88	0,51	1,05	0,81	1,07	0,73
Run 6	1,12	1,26	0,97	1,16	0,97	0,89	0,96	1,19	0,59	1,20	1,23
Run 7	1,18	1,14	1,09	1,02	0,60	0,62	1,11	1,05	0,89	0,77	0,84
Run 8	0,78	1,21	0,83	0,67	0,89	0,83	0,59	0,95	0,95	0,66	1,05
Run 9	0,59	0,95	0,88	0,49	0,98	0,83	0,82	1,09	0,82	0,95	1,16
Run 10	0,96	1,12	1,12	1,53	0,94	0,55	0,67	1,22	0,98	0,85	0,47
Average	**0,896**	**1,068**	**0,908**	**0,933**	**0,931**	**0,765**	**0,833**	**0,972**	**0,851**	**0,948**	**0,939**

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Idle Memory Footprint

HTTP Long Polling - Idle Memory Footprint

# clients	1	50	100	150	200	250	300	350	400	450	500
Run 1	28,47	29,63	30,15	30,38	30,47	30,71	30,74	31,19	31,41	31,43	33,30
Run 2	28,83	29,47	30,00	30,28	30,57	30,66	30,90	31,04	31,16	31,78	32,47
Run 3	28,62	29,46	30,07	30,21	30,43	29,88	30,81	31,04	31,16	31,53	32,08
Run 4	29,07	29,40	30,14	30,25	29,83	30,70	30,72	31,07	31,24	31,49	32,49
Run 5	28,81	29,44	30,04	30,16	30,58	30,67	30,87	31,13	31,27	31,48	32,52
Run 6	27,90	29,86	30,00	30,32	30,39	30,46	30,72	31,10	31,25	31,34	32,16
Run 7	28,73	29,80	29,93	30,18	30,50	30,77	30,99	31,19	31,23	32,26	32,38
Run 8	28,23	29,80	30,19	29,46	30,55	30,66	30,39	30,99	31,13	31,54	32,14
Run 9	27,10	29,49	30,13	30,35	30,45	30,41	30,87	31,13	31,36	32,54	32,40
Run 10	28,16	29,51	30,04	29,37	30,35	29,95	30,75	31,11	31,25	32,18	32,34
Average	**28,392**	**29,586**	**30,069**	**30,096**	**30,412**	**30,487**	**30,776**	**31,099**	**31,246**	**31,757**	**32,428**

Tekst

Server Sent Events - Idle Memory Footprint

# clients	1	50	100	150	200	250	300	350	400	450	500
Run 1	29,08	28,58	29,10	29,69	31,03	31,90	32,13	31,96	33,09	34,11	34,93
Run 2	27,51	28,73	30,47	30,80	30,95	31,10	31,33	31,77	33,11	34,03	33,77
Run 3	28,60	28,37	30,12	30,78	30,43	30,71	31,33	32,36	33,15	34,58	34,99
Run 4	29,12	28,34	30,19	29,26	30,99	31,29	31,40	31,92	32,97	34,01	34,98
Run 5	28,78	30,00	30,68	30,72	29,99	31,30	31,71	31,93	33,45	33,55	34,71
Run 6	28,71	30,10	28,98	30,83	29,91	31,02	31,55	31,89	32,99	33,67	34,87
Run 7	28,88	30,01	30,24	30,65	30,96	31,20	31,45	32,08	32,75	34,55	34,87
Run 8	29,16	28,49	30,48	30,72	30,82	31,29	31,42	31,79	33,26	33,70	35,02
Run 9	28,94	28,44	30,49	29,20	30,95	31,16	31,27	31,98	37,23	34,48	34,53
Run 10	28,72	29,84	28,71	30,58	30,97	31,30	31,36	32,83	32,94	34,22	35,13
Average	**28,75**	**29,09**	**29,946**	**30,323**	**30,7**	**31,227**	**31,495**	**32,051**	**33,494**	**34,09**	**34,78**

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WebSocket - Idle Memory Footprint

# clients	1	50	100	150	200	250	300	350	400	450	500
Run 1	17,76	21,15	22,89	23,50	24,05	27,08	28,70	29,89	32,25	32,37	34,24
Run 2	17,51	20,89	22,99	23,31	24,02	25,76	28,05	30,00	32,13	32,56	34,77
Run 3	17,59	20,93	22,41	23,53	23,84	25,80	28,09	29,91	32,15	32,49	34,10
Run 4	17,68	21,13	23,00	23,42	24,46	25,67	28,26	29,94	32,32	32,59	34,53
Run 5	17,82	21,23	23,08	23,51	24,04	25,86	28,31	29,93	32,06	32,52	34,46
Run 6	17,60	21,14	23,18	23,51	23,82	25,97	28,05	30,42	32,25	32,53	34,08
Run 7	17,98	20,92	22,80	23,56	24,05	25,67	28,16	29,92	32,14	32,56	34,47
Run 8	17,86	20,89	22,91	23,54	23,89	25,71	28,16	29,80	31,96	32,45	34,40
Run 9	17,86	21,22	22,72	23,50	23,89	25,73	28,11	30,05	32,31	32,46	34,25
Run 10	17,85	20,93	22,73	23,46	23,85	25,89	28,24	30,05	32,11	32,53	34,36
Average	**17,751**	**21,043**	**22,871**	**23,484**	**23,991**	**25,914**	**28,213**	**29,991**	**32,168**	**32,506**	**34,366**

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Idle Response Time

HTTP Long Polling - Idle Response Time

# clients	1	50	100	150	200	250	300	350	400	450	500
Run 1	3,26	3,11	2,96	3,14	3,15	3,15	3,98	3,00	2,96	3,08	3,10
Run 2	2,95	3,27	3,30	3,62	3,12	2,92	3,24	3,09	3,11	3,04	2,91
Run 3	3,05	3,30	3,20	3,12	3,02	3,15	3,19	3,16	3,04	2,98	3,14
Run 4	3,10	3,30	3,29	3,14	3,07	3,01	3,17	3,18	3,01	3,01	2,94
Run 5	3,08	3,40	2,98	3,12	3,00	3,02	3,15	3,08	3,14	3,10	3,10
Run 6	3,26	2,97	3,19	3,00	3,15	3,13	3,05	3,31	3,09	3,09	3,42
Run 7	2,97	3,84	3,25	2,97	3,00	3,01	3,13	3,27	3,20	3,15	3,07
Run 8	3,10	3,30	2,88	3,08	3,12	3,03	3,20	3,05	3,20	3,12	3,03
Run 9	3,06	3,34	3,13	2,93	3,15	3,05	3,07	3,11	3,10	3,04	2,97
Run 10	3,33	4,91	2,89	3,08	2,93	3,17	3,20	3,30	3,08	2,99	3,21
Average	**3,116**	**3,474**	**3,107**	**3,12**	**3,071**	**3,064**	**3,238**	**3,155**	**3,093**	**3,06**	**3,089**

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Server Sent Events - Idle Response Time

# clients	1	50	100	150	200	250	300	350	400	450	500
Run 1	3,20	3,36	3,18	2,91	2,92	3,39	2,85	3,21	4,05	2,95	3,07
Run 2	3,10	3,07	3,01	3,12	3,10	2,96	3,14	3,14	3,09	2,98	3,08
Run 3	3,17	3,32	3,10	2,95	3,13	3,15	2,90	3,16	3,07	2,88	3,21
Run 4	3,30	4,01	3,11	3,02	3,07	3,04	3,22	3,04	2,89	3,18	3,41
Run 5	3,32	3,02	3,15	2,98	3,11	3,06	3,18	3,10	3,04	3,01	3,56
Run 6	3,17	4,03	3,01	2,95	3,03	2,99	3,03	3,14	3,15	3,07	3,03
Run 7	3,17	3,19	3,19	3,04	3,00	3,06	3,02	3,05	3,08	3,18	3,14
Run 8	3,09	3,11	3,04	3,04	3,16	3,10	2,99	3,24	3,02	3,09	4,22
Run 9	3,27	4,35	3,13	3,07	2,99	3,17	3,11	3,07	3,03	2,98	3,07
Run 10	3,26	3,24	3,14	3,03	3,15	3,19	3,15	3,10	3,11	3,06	3,16
Average	**3,205**	**3,47**	**3,106**	**3,011**	**3,066**	**3,111**	**3,059**	**3,125**	**3,153**	**3,038**	**3,295**

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WebSocket - Idle Response Time

# clients	1	50	100	150	200	250	300	350	400	450	500
Run 1	1,32	1,40	1,44	1,35	1,38	1,49	1,48	1,41	1,42	1,48	1,41
Run 2	1,46	1,52	1,40	1,32	1,47	1,32	1,34	1,41	1,39	1,45	1,42
Run 3	1,27	1,50	1,39	1,46	1,38	1,34	1,39	1,40	1,31	1,46	1,41
Run 4	1,31	1,41	1,53	1,35	1,15	1,44	1,39	1,38	1,45	1,33	1,45
Run 5	1,40	1,35	1,35	1,37	1,18	1,45	1,33	1,37	1,28	1,37	1,47
Run 6	1,37	1,46	1,45	1,40	1,40	1,37	1,28	1,46	1,38	1,48	1,55
Run 7	1,46	1,49	1,44	1,30	1,40	1,38	1,38	1,43	1,38	1,42	1,32
Run 8	1,29	1,55	1,41	1,47	1,38	1,38	1,36	1,48	1,43	1,40	1,49
Run 9	1,41	1,59	1,54	1,27	1,52	1,35	1,33	1,39	1,33	1,45	1,58
Run 10	1,33	1,58	1,57	1,40	1,35	1,37	1,40	1,51	1,40	1,42	1,35
Average	**1,362**	**1,485**	**1,452**	**1,369**	**1,361**	**1,389**	**1,368**	**1,424**	**1,377**	**1,426**	**1,445**

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