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Toward the Concurrent Transportation Protocol for High Traffic Volume in 4G/5G Networks

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Abstract

The Transmission Control Protocol (TCP) was intentionally designed for the sake of service reliability but with the cost of application performance on which TCP clients need to use multiple connections to achieve concurrency and to reduce latency. And more importantly, it was designed mostly for the fixed networks and to transport traffic of non-real-time applications and thus not suitable for the mobile networks with higher packet error rate and real-time traffic. For example, TCP is a connection-oriented protocol, so it has to guarantee delivery of information, in order to maintain that connection. The recipient has to acknowledge the data that was sent and that creates overhead. It means that it's going to take more packets transferred, and thus higher delay. To address this weakness of TCP, and on this paper, we proposed a new application-level protocol that makes use of TCP as transportation, named as CoTCP (Concurrent request-response over TCP). The new proposed protocol allows sending and receiving multiple messages concurrently on one connection. We also evaluated and tested the performance of CoTCP in various application scenarios on the specific hardware platform. Numerical results show that CoTCP can lead to higher concurrency and lower latency.

Keywords: 4G/5G networks, CoTCP, TCP, concurrency, latency, high performance, high traffic.

1. Introduction

The mobile networks have gone through five generations from the first generation of analog technology to second generation of digital technology to 3rd, 4th and 5th generation of using IP technology. The transform in to IP-based network brings a lot of benefits to both network operators and service users in terms of multi-services, higher capacity, better (service) experience, etc. but it also comeses at a cost of performance degradation. That said, there are huge efforts from both academic and industrial sectors to bring in solutions to guarantee the carrier-grade performance and quality for the services of mobile users. One of the direction is to optimize the transport protocols and mechanisms in order to meet up with the real time traffic such as voice and video in 4th and 5th generation mobile networks. This paper is about to propose a new customized TCP-based protocol to accommodate this requirement in 4G/5G networks. But first let's have some basic understanding of the 4th and 5th generation networks.

4G network or the Long Term Evolution (LTE) Network called Evolved Packed System (EPS) is an end-to-end (E2E) all IP network; EPS is divided into two parts: radio access network (E-UTRAN) and core network (EPC). An E2E all IP network means that all traffic flows - from a UE all the way to a Packet Data Network (PDN), which connects to a service entity - are transferred based on IP protocol within EPS. EPC system includes Mobility Management Entity (MME), Serving Gateway (SGW) and PDN Gateway (PGW), more details are on [1, 2].

In EPC, MME is a logical entity responsible for authentication, session management and mobility management for the subscribers. It also connects E-UTRANS (eNodeBs) to EPC using the S1AP interface, which makes use of SCTP at the transport layer.

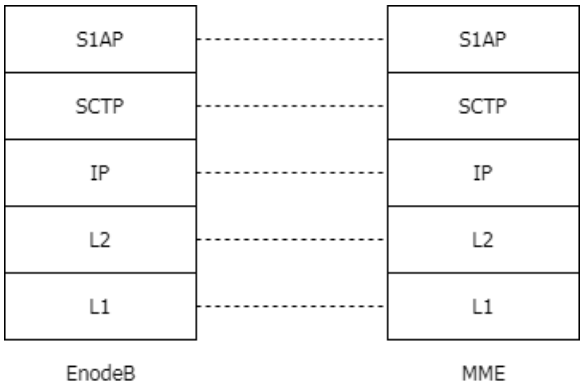

Fig. 1. S1: E-UTRAN-MME Interface

Requirements of the interface between MME and EUTRAN are as follows:

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- Single IP Service: MME have only one IP service for S1-MME Interface which is used to listen the connection from E-UTRAN.

- Number of connections: up to thousands of connections; in Viettel networks, one MME can manage over 17,000 SCTP connections with EUTRAN, each of EnodeB in EUTRAN can support 3000~5000 user subscribers.

- Ensuring High Availability

- Minimizing the impact when switching connections (crash system or support for maintenance).

After the 4G, 5G systems [3, 4] support interworking with Intranet networks or the Internet based also on the IP. To communicate and receive service on an IP network, a host must have an IP Address. In the 5G network, the host in question is the User Equipment (UE), and the Session Management Function (SMF) is responsible for allocating IP Addresses to the UE [5]. This can be either a static IP address or a dynamic IP address.

5G architecture is split into control and user plane to better manage networking and computing resources. The control plane (CP) includes network functions that manage signaling, subscription management, authentication and fees charging, and does not have high bandwidth, low latency requirements. The SMF is one such function and manages the establishment, modification and release of UE connectivity sessions, also called PDU (Protocol Data Unit) Sessions. The user plane (UP), on the other hand, handles user traffic which is deployed at the network edge to provide low latency, high bandwidth services. In traditional IP networks, the interworking with subnetworks or other IP networks is done with IP routers. From the perspective of the IP network interworking with the 5G network, the UP is seen as a normal IP router [2]. Therefore, the SMF must also allocate IP chunks - ranges of IP addresses - to the UP so that the UP may advertise and correctly route traffic from the network to the UE. The UE generally receives an IP Address that falls into the IP chunk of the serving User Plane Function (UPF).

To adhere to the cloud native architecture of the 5G Core, the SMF is made up of loosely coupled micro-services that splits functionality between each service. The IP Allocation service is one such micro-service that provides the function of allocating and managing IP Addresses for UE. A high level decomposition of the SMF is as follows: Layer 1 - Ingresses and Egresses services which act as gateways for other Network Functions and manage high availability and Load Balancing traffic between computing units; Layer 2 - Application and Logic core, a number of stateless software cores which handle the internal business logic of the SMF; and Layer 3 - the Database which keeps track of system state. The IP Allocation service resides in the Application layer while using the Database layer to maintain consistency

On IP networks, TCP is one of the most commonly used protocol that is designed to send packets across the Internet and ensures the integrity of data sent over the network [1, 2, 6]. In order to transmit data, TCP establishes a connection between a source and its destination. TCP can only transfer one message at a time per connection. A normal TCP transaction operated like this: client establishes a connection to server; client sends a request to server and wait for the response; server responses to client; the connection is closed or is reserved to be used for next transactions. A transaction needs to wait for other transaction to be completed before it can be started. A common strategy is to open multiple connections to serve multiple transactions at a time, which can help to improve concurrency and to reduce latency, but opening too many connections can be costly.

TCP uses a three-way handshaking to establish a connection between the client and the server [3]. A three-way handshaking process is expensive because it requires three packets (SYNC, SYNC-ACK, and ACK) to be transferred. To avoid having to open the connection many times, a TCP connection can be made persistent to be reused. However, additional resources are required to maintain each persistent TCP connection. Multiple TCP clients where each one opens several connections to the server can cause the server to be overloaded.

To address that weakness of TCP for the applications in 4G/5G mobile core networks, our R&D team has come up with a proposition of a new application protocol names as CoTCP. The CoTCP is designed to solve the concurrency problem of TCP and on our design, a CoTCP transaction is operated in asynchronous mode so that multiple ones can be executed concurrently over the same TCP connection thus makes CoTCP able to meet the requirement of high number of transactions per second (TPS) and low latency system while ensuring low number of (TCP) connections.

The rest of the paper is organized as follows. The investigation result of similar works will be given on Section 2. Section 3 will present the details of our new proposed application protocol, named as CoTCP. Experimental setup and performance evaluation will be presented in Section 4. Finally, Section 5 concludes our paper.

2. Related Works

On this section, we will discuss about current researches on the problem of high-performance TCP client-server system and how to scale up TCP for handling of large number of concurrent clients. This problem remains always the hot (research) topic for decades.

The C10K problem [7] was coined in 1999 by software engineer Dan Kegel. It is the problem of optimizing network sockets to handle 10,000 connections at the same time. C10K problem is currently solved by certain web servers such as Nginx [5] which applies event-driven architecture to disorder the execution flow of network programs and maximizes the utilization of CPU. By the early of 2020s, the problem is scaled up to C10M which means to concurrently handle 10,000,000 connections. Several solutions have been proposed to solve the C10M problem also, such as in [9, 10, 11]. Those solutions mainly focus on optimizing or bypassing the kernel and therefore utilize multi-core processors and reduce system calls and context switching overheads. Recently, there are high-speed packet I/O frameworks such as DPDK [12], netmap [13], and PF RING [14] that allow user-space applications to exchange packets with the kernel networking stack, providing unprecedented network performance for applications.

All of the above-mentioned solutions solve the concurrency problem of TCP by trying to increase the number of concurrent connections but none has been focused on utilizing a single connection to handle multiple (application) transactions concurrently. With the introduction of coroutine in modern programming languages such as Golang [15], Python, and Kotlin [17]; handling millions of transactions at the same time becomes significantly less expensive. Coroutine is a light-weight thread managed by user-space which allows execution to be suspended or resumed without context switching overheads [17]. Using coroutines, applications can easily handle millions of concurrent transactions but to open and to manage millions of concurrent connections is still a challenge to this day.

3. The Proposed Solution

3.1. Proposed Architecture

As said above, on this work, we've proposed a new application-level protocol to solve the concurrency problem of TCP. The new protocol was named as CoTCP (Concurrent request-response over TCP) and this section will give a detailed presentation of its design and operation.

The core part of new proposed protocol are its transactions. CoTCP transactions are designed asynchronously in which a request could be sent before the response of another request is received as depicted on Fig. 3.

In this asynchronous transaction mode, responses could be received out of the order in which requests were sent. To make this possible, we assigned each request with a unique identifier (ID) and then the corresponding response must have the same ID so that it can be matched to its own request. As such, the proposed structure of a CoTCP message is depicted as on the Fig. 4.

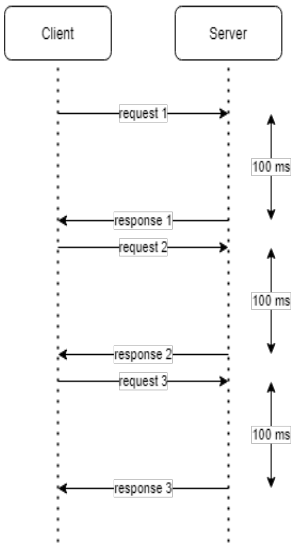

Fig. 2. Requests and responses are sent sequentially.

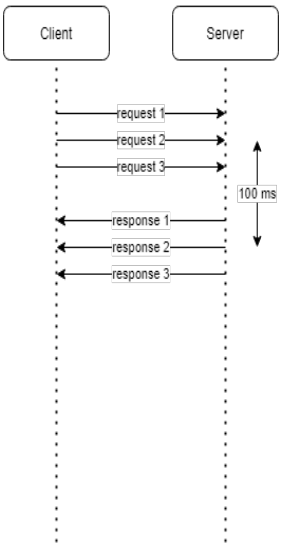

Fig. 3. Requests and responses are sent concurrently.

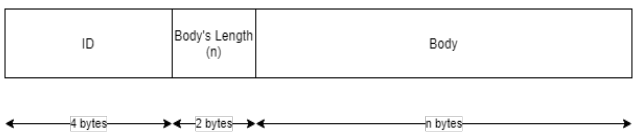

Fig. 4. Message's structure.

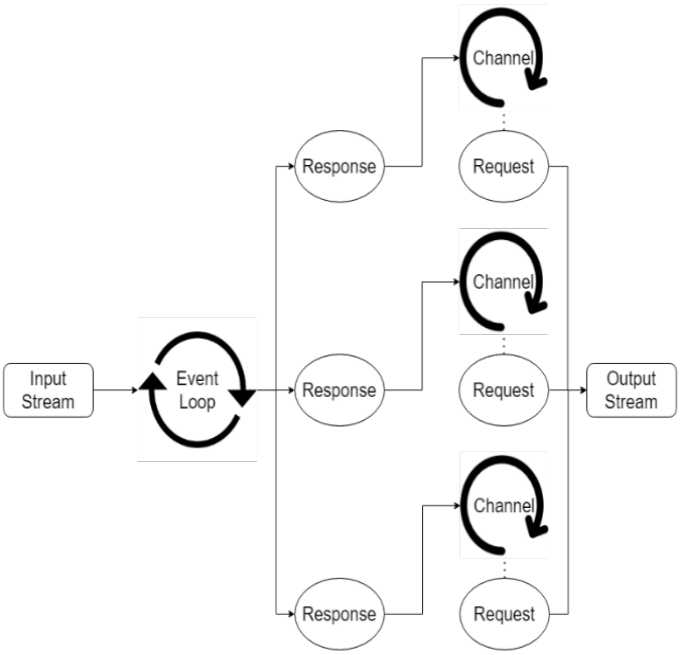

Fig. 5. Application architecture of CoTCP Client

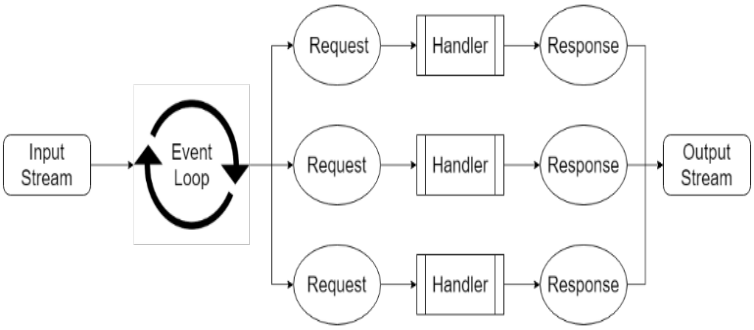

Fig. 6. Application architecture of CoTCP server

The message is composed of three parts:

- ID: A 4 bytes, unique integer that identifies a pair of request and response;
- Body's Length: A 2 bytes integer that indicates the size of message's body;
- Body: The actual content of the message that is stored in binary format.

The working procedure of CoTCP on client side is illustrated as in Fig. 5.

The procedure is a sequence of steps as follows:

- Step 1: Establish a new connection to the server;
- Step 2: Create an event loop to listen on the established connection;
- Step 3: Generate a unique ID for each request message;
- Step 4: Send request message and open a channel to wait for the response;
- Step 5: When the event loop receives data, split the data stream into messages and send them to the corresponding channels;
- Step 6: Read the response message from the channel and close the channel.

From the server side, the CoTCP working procedure is as depicted on the Fig. 6.

It also goes through steps as following:

- Step 1: Accept a new connection from the client;
- Step 2: Create an event loop to listen on the established connection;
- Step 3: When the event loop receives data, split the data stream into messages and handle them concurrently;
- Step 4: Assign the request's ID to the corresponding response and send response to the client.

3.2. Integration Works

In this sub-section, we will explain how to implement CoTCP client and server applications that can provide high concurrency and low latency with small overheads.

We choose Golang as the programming language to implement CoTCP because its built-in co-routines are suitable for building high concurrency applications.

The core of the CoTCP application is its event loop. Each TCP connection is managed by one event loop running on an independent coroutine. The responsibility of the event loop is to listen on the connection for incoming messages and to handle them concurrently. Since TCP transmits data in stream and there is no boundary between TCP packets, it has the problem of packets sticking together. In order to solve this problem, each CoTCP message has a length field that can be used to split the data stream into messages. For CoTCP server, the event loop will scan on the input data stream for request messages and will spawn a coroutine to handle each one; the response message is then sent back to the client through the same connection of its request. For CoTCP client, the event loop will scan on the input data stream for response messages and will send them to the corresponding waiting channels.

In order to match the response message to its request, each request is assigned to a channel that waits for response from the event loop. This mechanism makes a transaction look like a synchronous process. The list of waiting channels is stored in a hash table that can be used to lookup the channel by the ID of the response message.

4. Testing Results and Performance Evaluation

To evaluate the performance of the new protocol, we have setup the test-bed (Fig. 7) and conducted three performance benchmarks with different application configurations where each one was taken for both TCP and CoTCP.

The benchmarks were performed as following procedure:

- Step 1: Initiate the server with predefined configurations;
- Step 2: The server waits for incoming requests and responses after a delay;
- Step 3: Initiate the client with predefined configurations;
- Step 4: The client establishes a fixed number of connections to the server;
- Step 5: The client initiates a pool of worker coroutines to send request to the server and wait for the response;
- Step 6: The average number of transactions per second (TPS) and average latency is calculated where a transaction is started from the time of sending request until receiving response;
- Step 7: For TCP benchmark, transactions on the same connection are executed sequentially;
- Step 8: For CoTCP benchmark, transactions on the same connection are executed concurrently.

Each benchmark includes one server to handle requests and one benchmark tool acting as the client:

- The server is configurable with the following parameters: number of CPUs used, delay duration before sending responses back to the client, and size of the response's body;
- The client is configurable with the following parameters: number of CPUs used, number of opened connections to the server, number of worker coroutines used to send requests to the server, and size of the request's body.

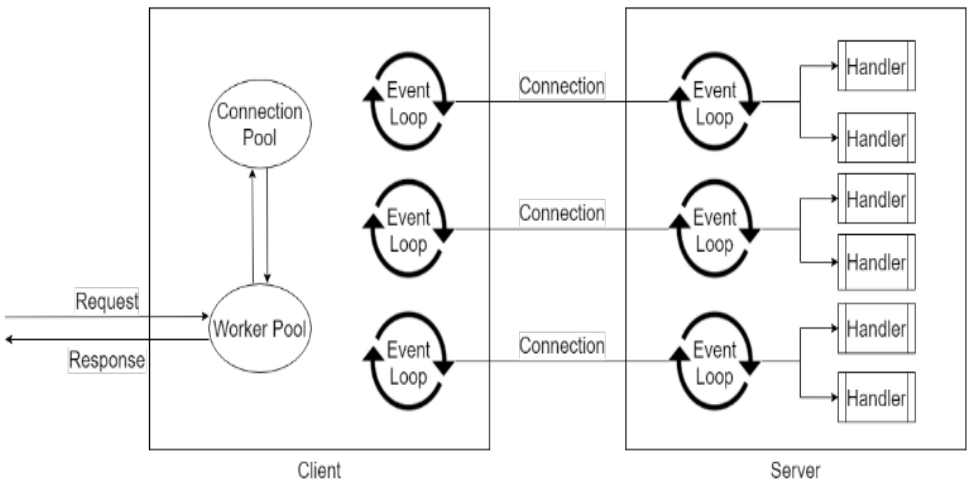

Fig. 7. Performance benchmark's setup.

4.1. First Benchmarking

4.1.1 Testing Configurations

This benchmarking test was designed to test the performance of CoTCP in comparison with TCP on the scenario that the number of connections from the client to server has increased from 1 to 500.

Table 1. Server's configurations

Parameter	Value
Type of CPU	Intel(R) Xeon(R) Gold 6242R CPU @ 3.10GHz
Number of CPUs	8
Reponse delay	0 ms
Size of response's body	10 bytes

Table 2. Client's Configurations

Parameter	Value
Type of CPU	Intel(R) Xeon(R) Gold 6242R CPU @ 3.10GHz
Number of CPUs	8
Number of worker coroutines	500
Size of request's body	10 bytes

4.1.2 Testing Results

According to Fig. 8 and Fig. 9, we can conclude that:

- For small number of connections (10 connections and below), the performance of CoTCP is about two times better than the performance of TCP;
- For big number of connections (100 connections and above), the performance of CoTCP is similar to the performance of TCP;
- The optimal number of connections for TCP is 500 which is equal to the number of worker coroutines; Increasing the number of connections beyond 500 will not improve the concurrency but produce idle connections;
- The optimal number of connections for CoTCP is about 10 connections; As the number of connections grows, the performance of CoTCP slightly decreases due to the overheads for maintaining extra connections.

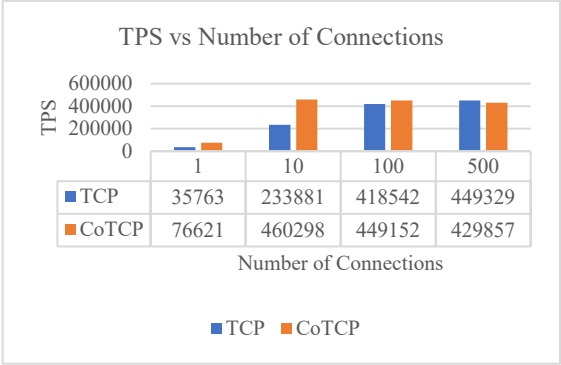

Fig. 8. TPS vs. Number of Connections

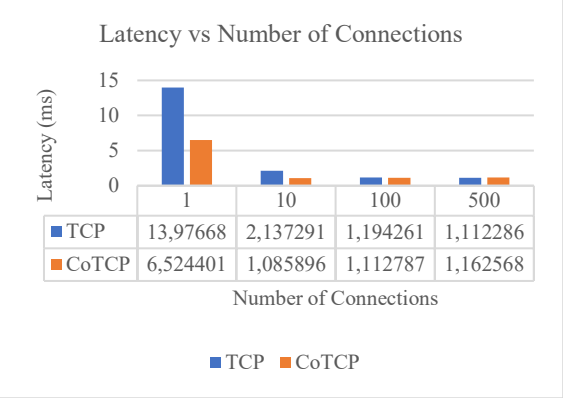

Fig. 9. Latency vs. Number of Connections

4.2. Second Benchmarking

4.2.1 Testing Configurations

This benchmarking test was designed with the difference to the first benchmarking which has the response delay increased from 0 to 10.

Table 1. Server's configurations

Parameter	Value
Type of CPU	Intel(R) Xeon(R) Gold 6242R CPU @ 3.10GHz
Number of CPUs	8
Reponse delay	10 ms
Size of response's body	10 bytes

Table 2. Client's Configurations

Parameter	Value
Type of CPU	Intel(R) Xeon(R) Gold 6242R CPU @ 3.10GHz
Number of CPUs	8
Number of worker coroutines	500
Size of request's body	10 bytes

4.2.2 Testing Results

According to Fig. 10 and Fig. 11, we can conclude that:

- The performance of TCP linearly increases as the number of connections increases from 1 to 500;
- The performance of CoTCP is the same for any number of connections.

At 500 connections, the performance of TCP is similar to the performance of CoTCP and is close to ideal which is 50,000 TPS and 10ms latency.

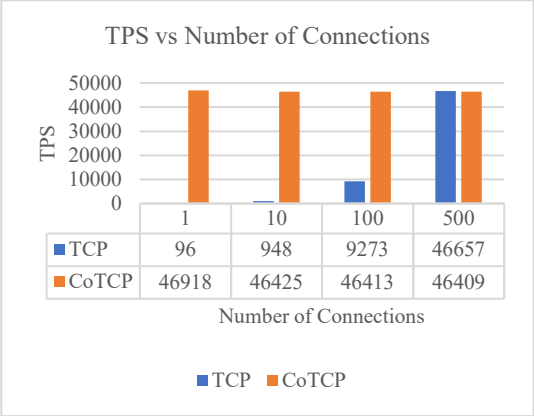

Fig. 10. TPS vs. Number of Connections

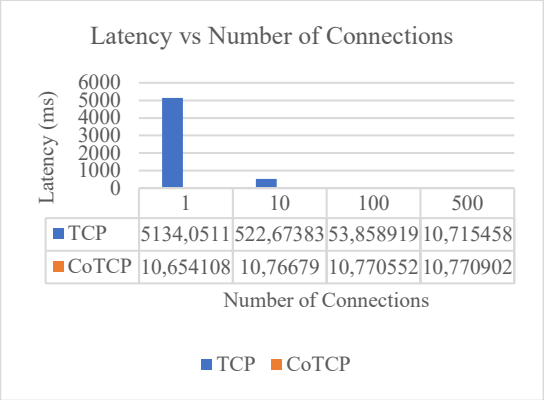

Fig. 11. Latency vs. Number of Connections

4.3 Third Benchmarking

4.3.1 Testing Configurations

This benchmarking test was designed with the difference to the second benchmarking which has the response delay increased from 10 to 100.

Table 1. Server's configurations

Parameter	Value
Type of CPU	Intel(R) Xeon(R) Gold 6242R CPU @ 3.10GHz
Number of CPUs	8
Reponse delay	100 ms
Size of response's body	10 bytes

Table 2. Client's Configurations

Parameter	Value
Type of CPU	Intel(R) Xeon(R) Gold 6242R CPU @ 3.10GHz
Number of CPUs	8
Number of worker coroutines	500
Size of request's body	10 bytes

4.3.2 Testing Results

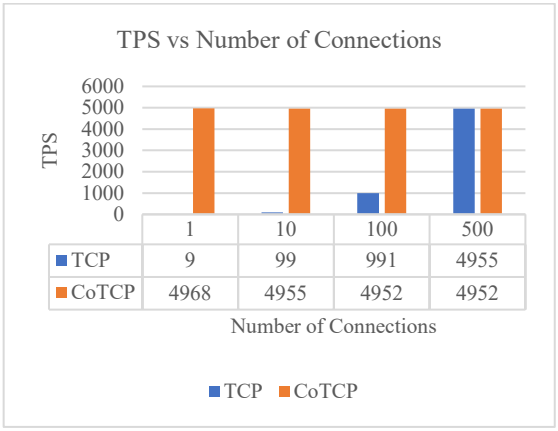

Fig. 12. TPS vs. Number of Connections

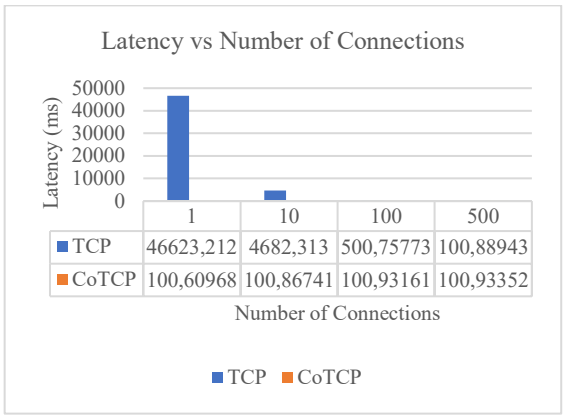

Fig. 13. Latency vs. Number of Connections

According to Fig. 12 and Fig. 13, we can conclude that even though we have inscrease the response delay of server from 10ms to 100ms, the results are still the same as on the second benchmarking at item 4.2. that is:

- The performance of TCP linearly increases as the number of connections increases from 1 to 500.
- The performance of CoTCP is the same for any number of connections.

At 500 connections, the performance of TCP is similar to the performance of CoTCP and is close to ideal which are 5000 TPS and 100ms latency.

5. Conclusion

On this paper, we have presented our work on proposing a new a protocol based on TCP named as CoTCP, which allows sending and receiving multiple messages concurrently over a single TCP connection. Numerical results show several advancements from our work as below:

- CoTCP allows to send requests and receive responses asynchronously over the same connection, therefore, it helps to improve concurrency and reduce latency without having to open many connections;
- In case the server can handle requests and response to the client immediately, which rarely happens in real conditions, the performance of CoTCP is not better than sending requests and receiving responses sequentially using TCP;
- In case the server needs a certain amount of time to handle requests and response to the client, the performance of CoTCP is much better than the performance of TCP for small number of connections; These become comparable as the number of connections grows.

The performance of CoTCP is less dependent on number of connections than the performance of TCP. The benchmark results show significant improvements in concurrency of CoTCP compared to TCP. However, there is still some limitation on the proposed protocol, for example, it does not support multiplexing capability [18, 19] on a single connection. Furthermore, while a large message is being sent, other messages are blocked from being sent over the same connection. In the future work, we will add that multiplexing feature to the CoTCP. In principle, to achieve multiplexing on a single connection, a CoTCP message must be divided in multiple parts before being sent. Parts of multiple messages will be mixed together and will be sent over the same connection. The server will receive messages' parts and combine them into complete messages.

6. Acknowledgement

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