Content

1. Introduction

1.1 Project Goal

The aim of this project is to design and implement DNS privacy protocol called “DNS/QUIC”. Domain Name System (DNS) networking protocol is widely used on the internet. This protocol is designed make accessing the website more human friendly. This protocol takes the website address (URL) on the web browser and converts it to an IP address, which will be returned to the web browser, then the desired web page will be assessed. Computers do not understand web names such as www.google.com. DNS was primarily designed for the ease of access of the web for humans. DNS converts website addresses to IP addresses. Internet users would have to remember IP addresses of web server that they desire to access if DNS did not exist.

1.2 Motivation

Networking security is essential in modern computing. While DNS is resolving web addresses to IP addresses, attackers could eavesdrop packets which are considered to be excessive. There are existing transport layer security protocols which encrypt or add integrity to DNS. QUIC (Quick UDP Internet Connection) is a transport layer network protocol is designed to be faster and having several advantages over other transport layer security protocols in theory. This project investigate and implement DNS/QUIC.

1.3 Report Structure

The Background chapter will provide the reader with the required background information to understand the architecture of DNS and QUIC protocols.

Popular and existing DNS privacy protocols will be outlined in the Literature Review chapter. Advantages and disadvantages of each protocol is will be discussed.

The architecture of DNS/QUIC will be discussed in detail in the Design chapter.

A prototype application for DNS/QUIC protocol was developed. This prototype application will be explained in detail in the Implementation chapter.

The result and timing of running DNS/QUIC is will be discussed and explained in comparison with other existing transport layer security protocols.

Potential improvements and enhancement that could be added to DNS/QUIC prototype will be proposed in the Future Work chapter.

Analysis of the project will be discussed in the Conclusion chapter.

2. Background

2.1 Transport Layer

The transport layer provides end-to-end communications for applications. There are two protocols are primarily used in transport layer:

1. **User Datagram Protocol (UDP)**

The User Datagram Protocol (UDP) is called a connectionless, unreliable transport protocol [1]. UDP adds a minimum overhead to the connection. This is due to the fact that UDP does not need to make connection establishment or termination. UDP does not add any error checking or congestion control, which makes the connection faster but unreliable for transferring important data. For example, if a packet get lost, then UDP will not request a retransmission of the lost packet. There are several protocols use UDP and and add reliability at the application layer. UDP is used to send and receive a small packets is size. We conclude that UDP is used for establishing low latency connection.

2. **Transmission Control Protocol (TCP)**

The Transmission Control Protocol (TCP) is a connection oriented protocol [1]. TCP has flow, error and congestion control. All layers below TCP in the OSI stack are unreliable for end-to-end communication. IP discard packets while sending if an error occurred. TCP/IP is widely used, but there are other protocols that use TCP, but not IP such as FIle Transfer Protocol (FTP) and Simple Mail Transfer Protocol (SMTP).

Layer	Function	Example
Application (7)	Services that are used with end user applications	SMTP,
Presentation (6)	Formats the data so that it can be viewed by the user Encrypt and decrypt	JPG, GIF, HTTPS, SSL, TLS
Session (5)	Establishes/ends connections between two hosts	NetBIOS, PPTP
Transport (4)	Responsible for the transport protocol and error handling	TCP, UDP
Network (3)	Reads the IP address form the packet.	Routers, Layer 3 Switches
Data Link (2)	Reads the MAC address from the data packet	Switches
Physical (1)	Send data on to the physical wire.	Hubs, NICS, Cable

Figure 2.1: The OSI stack defines a networking framework to implement protocols in layers

TCP provides a connection oriented protocol to the application layer. It enables reliable communication on account of the fact that if a packet is lost or corrupted, then TCP is responsible for handling retransmission. It is regarded as a connection-oriented because all state transition are communicated to the two parties of the connection. TCP does not precisely know when to retransmit data, hence it uses acknowledgment packets for determining whether retransmission is required or not. In TCP, the connection must be established prior to transmission, unlike UDP which does not to establish connection prior to transmission. TCP is reliable, but it has a high latency connection due to its reliability on delivering packets.

2.2 Transport Layer Security (TLS)

Transport Layer Security (TLS) encrypts data that sent over the internet. It provides end-to-end privacy and data integrity between two communicating applications. TLS has a layer called “TLS Handshake Protocol” which will be discussed in detail in Chapter 3. TLS is used in the application layer to provide privacy. For example, it could be used to secure DNS. TLS is implemented on top of TCP due to its reliability. Reliable medium is required, because an error or data corruption occurring during TLS handshake will result in failure of establishing the connection; however, TLS has been implemented on top of UDP as well. There are situations in which UDP is preferable and TLS is used to secure the connection and it is called “DTLS” protocol.

2.3 Domain Name System (DNS)

The Domain Name System (DNS) is an application layer protocol which runs on top of UDP. It is responsible of converting alphabetic web addresses to IP addresses, which computers use to connect to the desired web server which has the requested web page. Running DNS on top of UDP does not add data integrity or encryption to the packets and it is called “plain DNS”; however, DNS/DTLS protocol adds data integrity and encryption. Also, DNS could run on top of TCP and TLS to provide privacy and encryption and it is called “DNS/TLS”. These two protocols are already exist and will be discussed in Chapter 3.

2.3.1 Domain Name Space

The Internet is growing rapidly, and the number of users is increasing; hence, there are a huge number of web servers. Those servers are mapped using their name spaces to the corresponding IP addresses. Name spaces must be unique to be mapped correctly to the corresponding IP address to avoid ambiguity. Names are organised in a hierarchical structure.

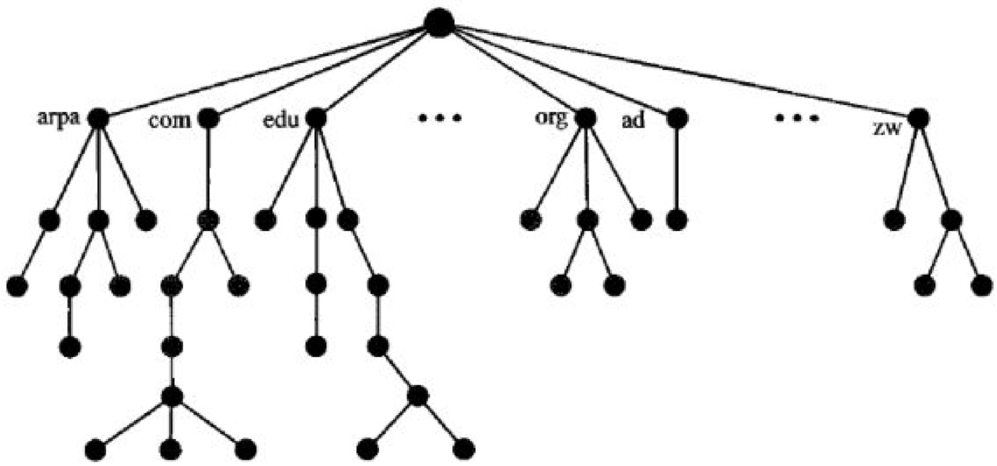


Figure 2.3.1: Domain Name Space hierarchical architecture

The hierarchical is an inverted binary tree. It has the maximum of 128 nodes. The first node on top of the tree is called “root”. Each node has a label. Parent nodes could have multiple children nodes. Children of a node have labels, but each label must be unique, which guarantees unambiguity of domain names. Each node in the tree has a domain name. A full domain name is a sequence of labels separated by dots(.)[1]. The next level of the tree is called Top Level Domains (TLD). This layer has .com, .org and etc. Domains are a subtree of the domain name space, and the name of the domain is the name of the node on top of the subtree.

2.3.2 Resolution

Converting or mapping name to IP address is called “address resolution”. DNS is designed in client-server architecture. The host which request a mapping from a name to IP address is called a “resolver”. The resolver calls the closest DNS server, if that server could do the mapping, then it resolves the query and sends it back to the resolver. Otherwise, it asks other servers to resolve the query.

2.3.3 Recursive Resolution

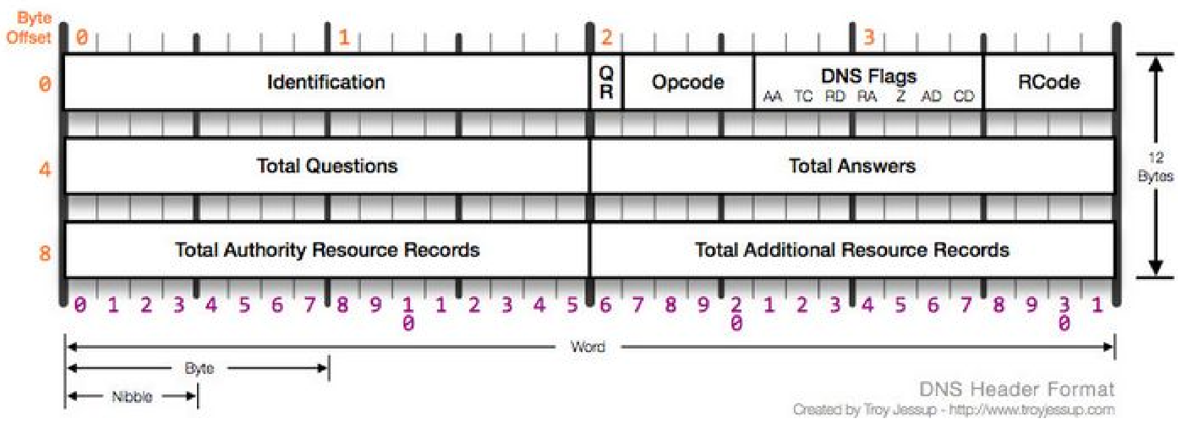
In DNS, there are few types of servers: stub, authoritative, and recursive. Stub servers usually initiate DNS queries. Authoritative servers store DNS record information. A resolver ask a DNS server to resolve name to IP address. If the server is an authority server of the domain name, then it search its database and returns an answer. Otherwise, it sends the request to another DNS server and waits for a response. This process is repeated until it reaches an authoritative server which finally replies with an answer. The response from the authoritative server travels back to the resolver. This process is called “recursive resolution”, and server which send DNS requests to another server searching for a response are called “Recursive servers”.

2.3.4 DNS Cache

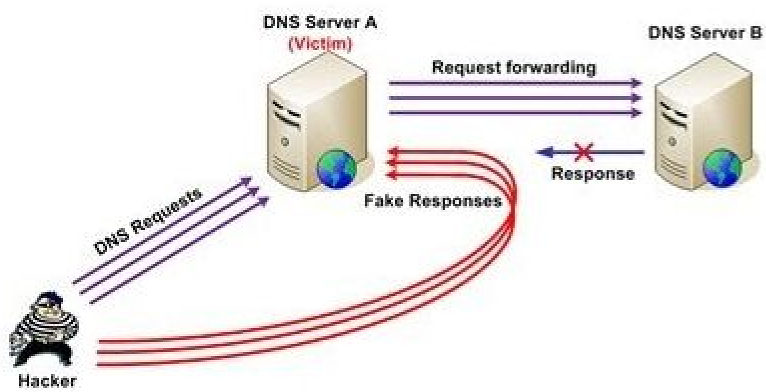
DNS has caching, which will cause a reduction in time for mapping names to IP addresses through recursive resolution. DNS resolver requests an answer for a query, and this response will be cached, so the resolver will not have to resolve names using recursive resolution, which will be more efficient. Authoritative servers always adds information called “time-to-live”. This information defines the time in seconds that the receiving server can cache the information[1]. After this time elapses, cached information will be expired and the query must be sent again to the authoritative server[1].

2.3.4 DNS Architecture

DNS has two different types of messages: query and response[1]. DNS query packet consist of header and question section; the response packet consist of header, answer record, authoritative record, and additional records. The header part in both query and response packet is identical.



The identification field is for the client to match the query and response identification number. Both query and response must have the same identification number to be accepted at the client. Otherwise, response will be dropped. This check is mainly for security reasons to prevent DNS cache spoofing.



DNS resolver could sent a query and an attacker could also eavesdrop the connection and send invalid or incorrect DNS record information to the resolver before it gets a response from an authoritative or recursive server. This information will be cached and everytime the resolver tries to resolve that name to IP address will get the incorrect mapping. This is called DNS cache spoofing. DNS header has identification field which randomly assigned to the DNS query, and the resolver will not accept any response that does not match its identification number in the query. This limits cache poisoning because attackers will have to guess this random identification number to be able to spoof the cache. The QR field identifies whether the message is query or response. The standard port to run DNS on is 53 on both UDP and TCP; however, other ports could be used.

2.4 Quick UDP Internet Connection (QUIC)

Quick UDP Internet Connection (QUIC) protocol is a secure transport layer protocol which runs over UDP. This protocol was designed to be secure and and flexible, and having several advantageous over other secure transport protocols such as TLS and DTLS. QUIC aims to have low-latency connection establishment, authenticated and encrypted payload, and stream multiplexing. QUIC uses TLS handshake to establish the connection. The specification of QUIC and the design of the protocol will be discussed in detail in Chapter 4.

3. Literature Review

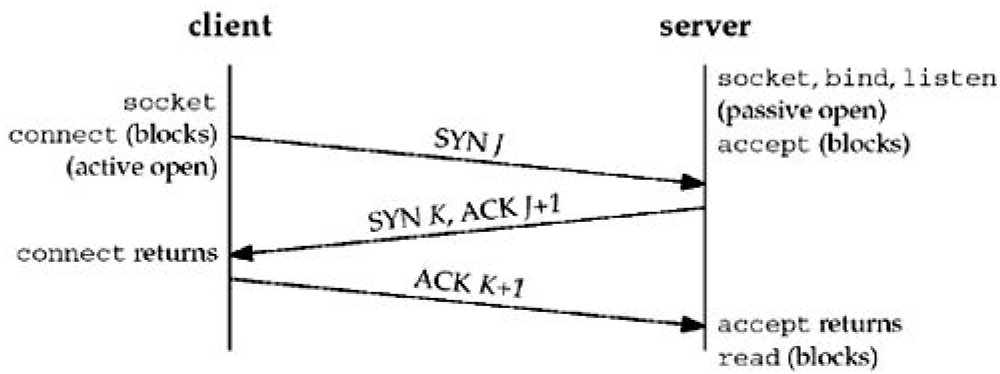
There are several existing protocols which provide secure connection for DNS. In this chapter, these protocols will be discussed in detail.

3.1 DNS/TLS

The standard is to run DNS over UDP, but it does not provide a secure connection. In order to secure DNS, TLS is used. Each step of running DNS/TLS will be discussed and explained.

3.1.1 TCP Session Establishment

DNS server listens and establishes TCP connection on the designated port which is 853, unless it has an agreement with the client to use other port for running DNS-over-TLS [2].

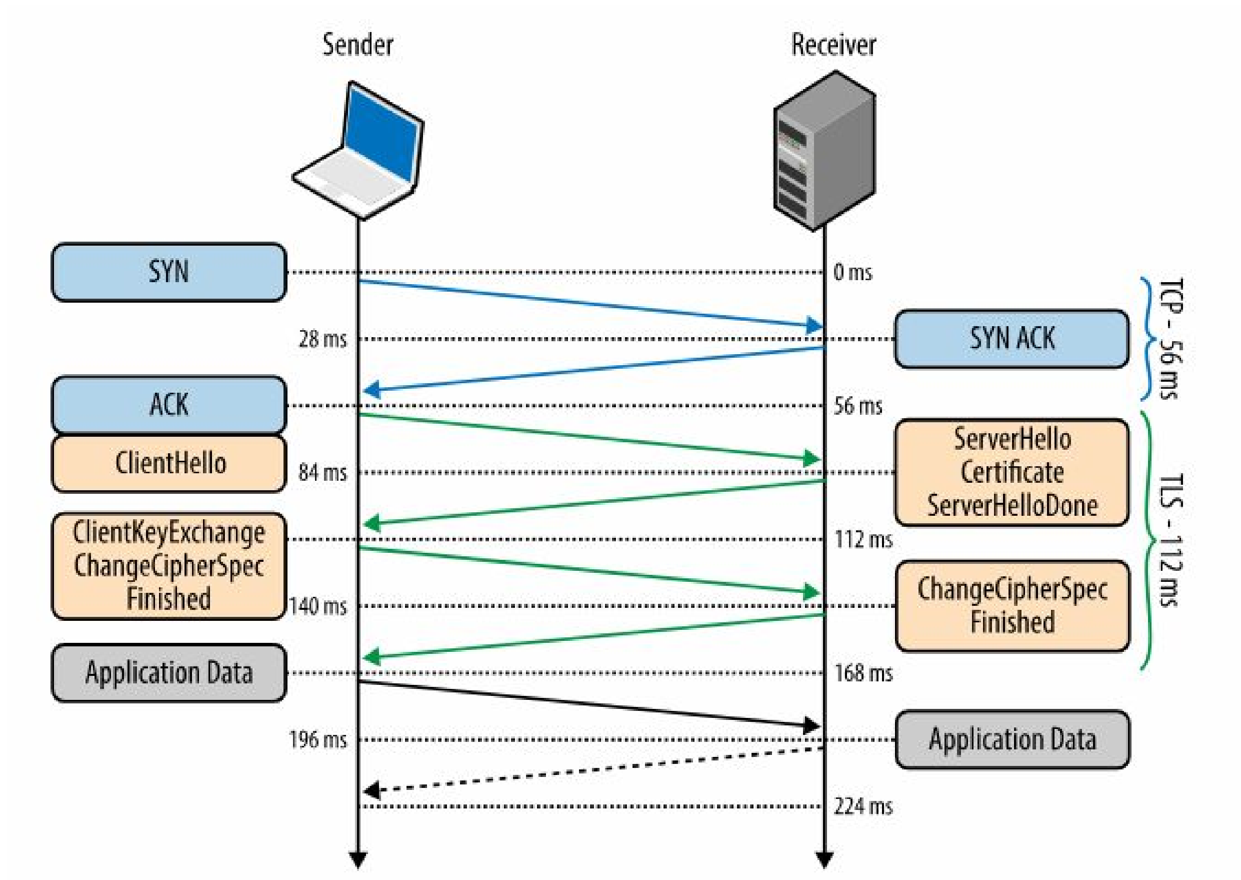


TCP three-way handshake establishes TCP connection between client and server. The client sends synchronize (SYN) segment with client's initial sequence number (denoted as "J" in the above diagram). Server listens to the client and replies with a synchronize (SYN) with the server's initial sequence number (K), also an acknowledgement (ACK) is sent with the client's initial sequence number incremented by 1 all in one segment. Then, the client replies with an acknowledgement (ACK) and the client's initial sequence number incremented by 1. At the end of this process, the TCP connection is established. It is three-way handshake because each side of the connection need to verify that they can transmit and receive segments, unlike two-way handshake where only the client can send data and the server acknowledges it, but never get the chance to transmit data. Now, the TCP connection is established and ready for transmitting data.

3.1.2 TLS Handshake

The TLS handshake is used to authenticate client and server on their first communication. Once client and server success communicating via TCP, then they proceed with the TLS handshake

[3]. The use of public and private key pair is the basis of the authentication. The public key is made accessible for the public. The private key is remain confidential for its owner. If a client and a server want to establish a secure connection and send encrypted data, then the client uses the server's public key to encrypt, and the server uses its private key to decrypt data.



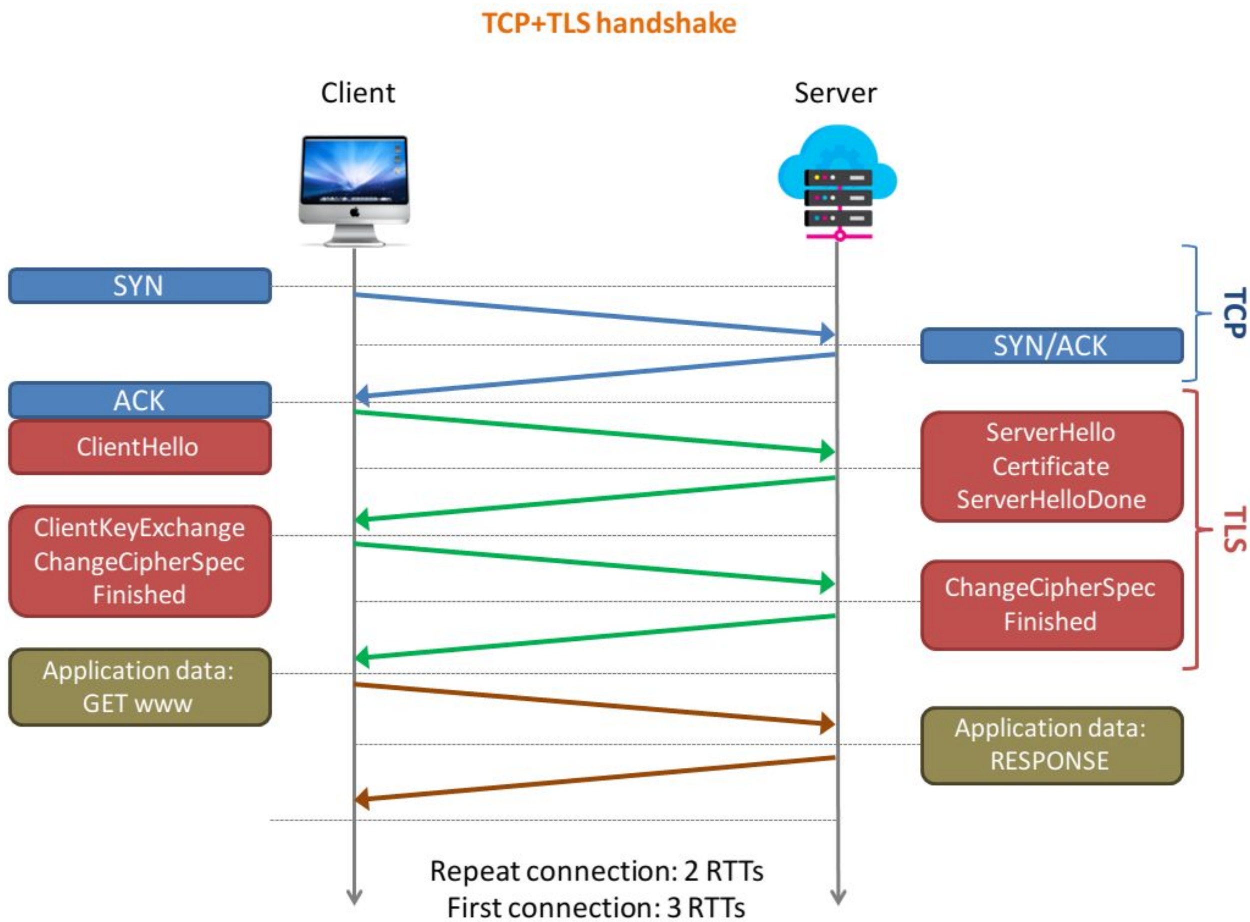
Client sends in clear text the specification of the TLS protocol. It sends the version of TLS protocol it uses, and supported ciphersuites it may use. Then, the server sends its certificate which has the server's public key to the client for authentication. The client sends its private key encrypted with server's public key. Then, both client and server send finish segment, then both will be ready now for transmitting and receiving encrypted data.

3.1.3 Transmitting and Receiving packets

Once the TCP connection and TLS handshake are established, then DNS client are server are ready for transmitting and receiving encrypted queries and responses. The DNS client send a query to the DNS server which either has the associated IP address of the host name in the cache or the server will have to use recursion resolution to get a response.

3.1.4 Performance Concerns

Running DNS-over-TLS has few performance concerns such as latency and processing time. In this project, we are mainly concerned with the latency concerns.



Running DNS/TLS will add additional Round Trip Time (RTT) of latency for establishing TCP connection, and another two RTTs for the TLS handshake on the first communication between client and server (DNS client and server). In total, it takes 3 RTTs on first connection, and 2 RTTs on repeat connection, because TLS session resumption can only start after TCP connection is established. Plain DNS does not add any latency because it uses UDP; hence, there will be no need to establish TCP connection or making TLS handshake since plain DNS is not encrypted. TCP suffers from network head-of-line blocking, where the loss of a packet causes all other TCP segments to not be delivered to the application until the lost packet is retransmitted [4].

3.1.5 Security Concerns

(Do it later)

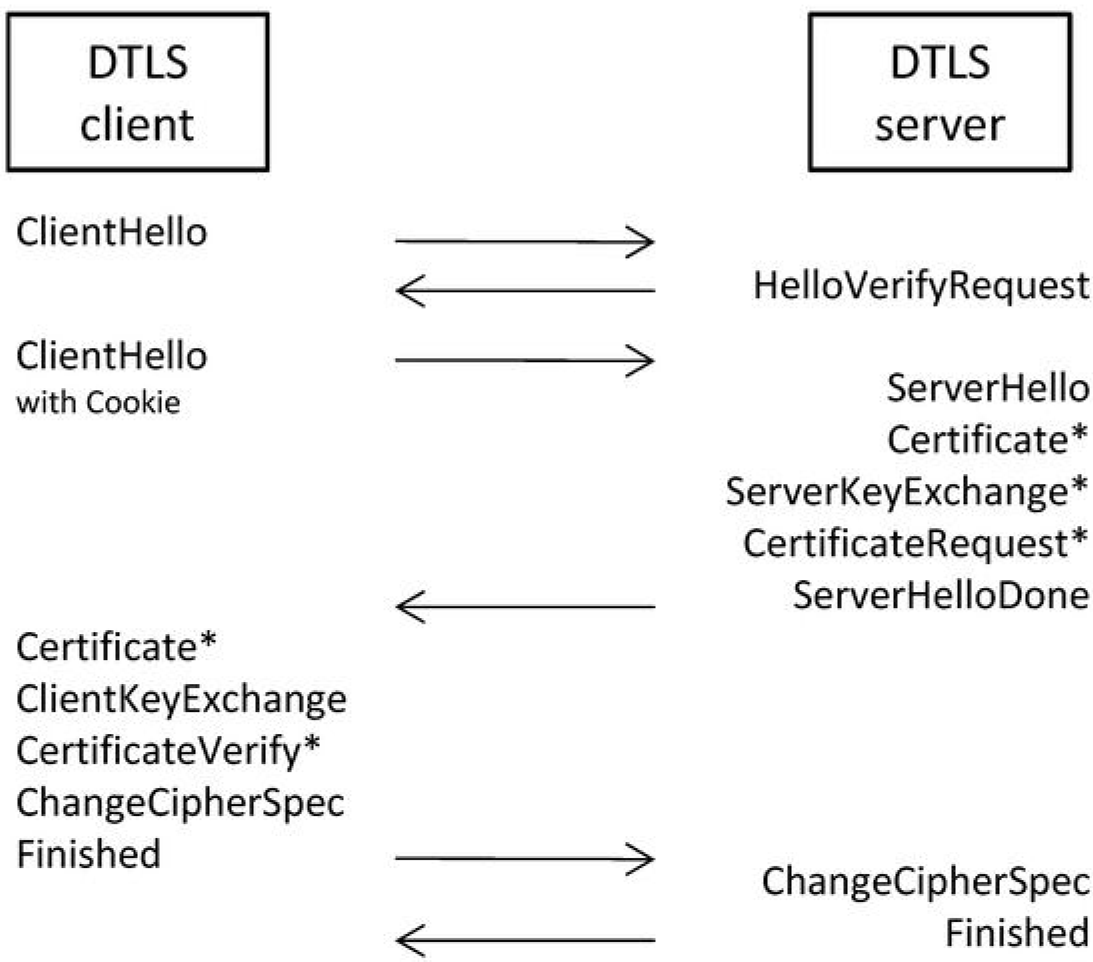
3.2 DNS/DTLS

Many application layer protocols prefer to use UDP due to its unreliability which makes the connection faster; therefore, DTLS was designed and implemented to provide privacy and integrity by encrypting datagrams of UDP. DTLS protocol uses TLS, but it modifies the original protocol. DTLS allows a retransmission of handshake messages to deal with the unreliability of UDP connection. DTLS does not suffer from network head-of-line blocking since it runs on top of UDP. Each step of running DNS/DTLS will be discussed and explained. DTLS message size is considered to be an issue. Usually TLS and DTLS handshake messages can be large and could go up to 2^24-1(many kilobytes). On the other hand, UDP datagrams are quite small. To compensate this problem and make the DTLS datagrams fit for the desired payload length as well, each DTLS handshake message contain both fragment offset and fragment length, then the recipient can reassemble all fragmented datagrams without using IP fragmentation which is very undesired because it adds an overhead [4].

3.2.1 Session Initiation

DNS-over-DTLS runs over the designated port, which it 853, unless client and server agree to use different port. DNS client checks if the DNS server supports DNS-over-DTLS by sending DTLS ClientHello to the server. If the server does not support DNS/DTLS, then it will not respond the DTLS ClientHello message. In that case, the client should retransmit DTLS Client hello, but it should stop after 15 seconds if the server does not respond.

3.2.2 DTLS Handshake



DTLS handels packet loss by allowing retransmission of handshake messages. This is done by adding a timer on ClientHello and ServerHello messages. The HelloVerifyRequest uses stateless cookie to handle and prevent denial of service (DoS) attack. The denial of service (Dos) is a cyber attack makes network resource unavailable to its users by flooding the victim server by sending malicious requests to overload it. In DTLS handshake, server send a stateless cookie, then the client receives it and has to send it back for authentication. This is a simulation of a three-way TCP handshake. After DTLS client and server authentication, ciphersuites and server's public key is exchanged, and this is similar to TLS handshake when private and public key pair is used for authentication.

3.2.3 Transmitting and Receiving packets

Once DTLS handshake is done successfully, then all data sent will be encrypted and attackers will not be able to eavesdrop packets or inject bogus DNS responses.

3.2.4 Performance Concerns

Running DNS-over-TLS suffers for the head-of-line blocking, unlike running DNS-over-DTLS because it runs on top on UDP. DTLS session resumption takes 2 RTT whereas TLS session resumption can only start after TCP handshake is complete [4]. Now, we can revisit the DTLS messages size and what potential performance issues does it add on DNS/DTLS. In comparison to plain DNS, running DNS-over-DTLS adds at least 13 octets (the octets is a telecommunication unit consist of 8 bits) of header, cipher and authentication overhead to every query and response. This will reduce the size of DNS payload that can be carried [4]. DNS client must inform the DNS server the maximum DNS response size it can re-assemble and deliver to the DNS client’s network stack [4]. The server must consider the amount of expansion expected by the DTLS processing when calculating the size of DNS response response that fits within the path MTU [4]. If the DNS response exceeds the pre-calculated length that can fit within DTLS datagram (path MTU), then the DNS server informs the client, then the DNS client must a new DNS request over an encrypted transport such as DNS-over-TLS, which adds one or two RTTS of latency [4].

3.2.5 Security Concerns

One of the main security concerns that involved in running DNS/DTLS is the downgrade attack. As described above in the performance consideration section, sometimes running DNS/DTLS cannot be done due to the message size, and DNS/TLS must be used. In the worst case scenario where client or server do not support DNS/TLS, then they may fallback to use clear text to get a response. DNS clients keep track of servers that known to support DTLS to avoid downgrade attacks.

4. Protocol Design

4.1 Protocol Overview

In this chapter, the design of QUIC protocol will be discussed in detail, then the design of running DNS-over-QUIC will be discussed.

4.2 QUIC Protocol Design

Quick UDP Internet Connection (QUIC) is a multiplexed and secure transport protocol which runs on top of UDP. QUIC protocol aims to flexible set of features that allow it to be a general-purpose secure transport for multiple applications [5]. QUIC has a set of features which are considered to be advantageous over other secure transport protocols. QUIC aims to provide low-latency connection establishment, authenticated and encrypted header and payload, stream and connection-level flow control, and stream multiplexing [5]. QUIC provides the same DNS privacy protection that DNS/TLS provides. QUIC is specifically designed to reduce latency by supporting 0-RTT data during session resumption, also it prevents head-of-line blocking by allowing parallel delivery on multiple streams of data using stream multiplexing technique. Currently, the only mapping defined with an application is HTTP-over-QUIC.

4.2.1 Using Transport Layer Security (TLS) to Secure QUIC

QUIC is secured using TLS version 1.3. TLS version 1.3 has various advantages from previous versions. It provides latency improvement for connection establishment, and first time connections can be established within 1 round trip (RTT); moreover, on subsequent connections between the same client and server , the client can transmit data immediately using 0-RTT feature.

4.2.1.1 TLS Handshake

TLS version 1.3 provides two basic handshakes that provides QUIC with latency improvement for connection establishment. Full 1-RTT handshake which the client is able to send application data to server after one round trip (1-RTT). The second handshake is 0-RTT handshake, the client uses information that has already learned about the server to send application data immediately with no latency. Zero RTT is only available if the client and serve have previously communicated [6]. QUIC has multiple streams to transmit and receive data simultaneously and prevent the head-of-line blocking. QUIC reserves and uses stream 0 for TLS connection. QUIC permits client to send frames to streams,and the initial packet from client a stream frame for stream 0 which contains the first TLS handshake message.

```
Client                                                          Server

Get Handshake
0-RTT Key Ready
                      --- send/receive --->
                                                    Handshake Received
                                                       0-RTT Key Ready
                                                         Get Handshake
                                                      1-RTT Keys Ready
                     <--- send/receive ---
Handshake Received
Get Handshake
Handshake Complete
1-RTT Keys Ready
                      --- send/receive --->
                                                    Handshake Received
                                                         Get Handshake
                                                    Handshake Complete
                     <--- send/receive ---
Handshake Received
Get Handshake
```

(Write more later on)

4.3 DNS/QUIC Protocol Design

There are different scenarios for using DNS protocol, and they can be classified in three different groups: stub to recursive resolver, recursive resolver to authoritative server, and server to server [7]. The design of DNS/QUIC only focuses on the stub to recursive resolver scenario.

<Insert Diagram>

5. DNS/QUIC Implementation

5.1 Implementation Overview

5.2 UDP Tunneling

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