HTTPA/2: a Trusted End-to-End Protocol for Web Services

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Abstract

With the advent of cloud computing and the Internet, the commercialized website becomes capable of providing more web services, such as software as a service (SaaS) or function as a service (FaaS), for great user experiences. Undoubtedly, web services have been thriving in popularity that will continue growing to serve modern human life. As expected, there came the ineluctable need for preserving privacy, enhancing security, and building trust. However, HTTPS alone cannot provide a remote attestation for building trust with web services, which remains lacking in trust. At the same time, cloud computing is actively adopting the use of TEEs and will demand a web-based protocol for remote attestation with ease of use. Here, we propose HTTPA/2 as an upgraded version of HTTP-Attestable (HTTPA) by augmenting existing HTTP to enable end-to-end trusted communication between endpoints at layer 7 (L7). HTTPA/2 allows for L7 message protection without relying on TLS. In practice, HTTPA/2 is designed to be compatible with the in-network processing of the modern cloud infrastructure, including L7 gateway, L7 load balancer, caching, etc. We envision that HTTPA/2 will further enable trustworthy web services and trustworthy AI applications in the future, accelerating the transformation of the web-based digital world to be more trustworthy.

Keywords— HTTP, HTTPA, TLS, Protocol, Attestation, TCB, TEE, Secret, Key Exchange, Confidential Computing

1 Introduction

We received positive feedback and inquiries on the previous version of HTTPA [12] (HTTPA/1). As a result, we present a major revision of the HTTPA protocol (HTTPA/2) to protect sensitive data in HTTPA transactions from cyber attacks. Comparatively, the previous work [12] is mainly focused on how to include remote attestation (RA) and secret provisioning to the HTTP protocol with Transport Layer Security (TLS) protection across the Internet, which is great, but it comes at a price. In contrast, HTTPA/2 is not necessary to rely on the TLS

protocol, such as TLS 1.3 [21], for secure communication over the Internet. The design of HTTPA/2 follows the SIGMA model [14] to establish a trusted (attested) and secure communication context between endpoints at layer 7 (L7) of the OSI model. Different from connection-based protocols, HTTPA/2 is transaction-based in which the TEE is considered to be a new type of requested resource over the Internet. In addition to protecting sensitive data transmitted to TEE-based services (TServices), HTTPA/2 can potentially be used to optimize the end-to-end performance of Internet or cloud backend traffic,

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thus saving energy and reducing the operational costs of Cloud Service Providers (CSPs).

HTTP is a predominant Layer 7 protocol for website traffic on the Internet. The HTTPA/1 [12] defines an HTTP extension to handle requests for remote attestation, secret provisioning and private data transmission, so Internet visitors can access a wide variety of services running in Trusted Execution Environments (TEEs) [11] to handle their requests with strong assurances. In this way, visitors' Personally Identifiable Information (PII) and their private data are better protected when being transmitted from a client endpoint to a trusted service endpoint inside the TEE. The HTTPA/1 supports mutual attestation if both client and service endpoints run inside the TEE. Although HTTPA/1 helps build trust between L7 endpoints with data-level protection, HTTPA/1 needs TLS to defend against attacks over the Internet, e.g., replay attacks and downgrade attacks. Note that TLS cannot guarantee endto-end security for the HTTPS message exchange [1] when the TService is hosted behind a TLS termination gateway or inspection appliance (a.k.a. middle boxes). Despite the fact that TLS provides confidentiality, integrity and authenticity (ConfIntAuth) to ensure secure message exchange for the HTTPA/1 protocol, it is not a complete end-to-end security solution to serve web services at L7. For example, TLS termination on the middleboxes makes it highly vulnerable to cyber-attacks. Both HTTPA/1 and TLS need to generate key material through key exchange and derivation processes. This requires additional round trips at L5 and increases network latency. Thus, there is room to further optimize the network performance and reduce communication complexity by avoiding the repetition of key negotiations. Due to the limitation of TLS mentioned above, a version of HTTPA with message-level security protection is a natural candidate to address the issues mentioned above at once.

This paper proposes an upgraded protocol, HTTPA/2, which makes it possible to secure

HTTPA transactions even with no underlying presence of TLS. HTTPA/2 is designed to improve the processes of key exchange, RA and secret provisioning in HTTPA/1. It also enables end-to-end secure and trustworthy request/response transactions at L7, which is cryptographically bound to an attestable service base that can be trusted by Internet visitors regardless of the presence of untrusted TLS termination in between.

The rest of the paper is organized as follows. Section 2 provides necessary preliminaries. Section 3 elaborates on the protocol transactions. Section 4 talks about security considerations. Section 5 concludes the whole paper.

2 Technical Preliminaries

This section provides preliminaries related to the construction of HTTPA/2. We first introduce using a Trusted Execution Environment (TEE) in a web service setting. Then we describe several important primitives to be used for constructing the HTTPA protocol described in section 3.

2.1 Trusted Execution Environment (TEE)

In a TEE, trustworthy code is executed on data with CPU-level isolation and memory encryption inaccessible to anyone even those with systemlevel privileges. The computation inside the TEE is protected with confidentiality and integrity. A TEE is more trustworthy than a Rich Execution Environment (REE) [5] where codes are executed on data without isolation. Although most web services are deployed in REE, it is an emerging trend to deploy web services in a TEE for better security. Upon implementation, a service initialized and run inside the TEE is known as a Trusted Service, called a TService. TService uses TEE to effectively reduce its trusted computing base (TCB), which is the minimal totality of hardware, software, or firmware that must be trusted for security requirements,

thus reducing the attack surface to as minimal as possible.

For some TEE, such as Intel[®] Software Guard Extensions (Intel[®] SGX) or Intel[®] Trust Domain Extensions (Intel[®] TDX), it can provide evidence (or we call the evidence "Attest Quote (AtQ)" in the section 2.2) reflecting configuration and identities [8] to the remote relying party. After successfully verifying the evidence and being convinced of the result, both parties finish the RA process [2] [20]. With the RA completed successfully, TServices can be shown more trustworthy to its relying party.

Not all TEEs are attestable, and the HTTPA is only applicable to attestable TEE which can generate such evidence for the purpose of RA.

2.2 Attest Quote (AtQ)

AtQ is an opaque data structure signed by a Quoting Service (QService) with an attestation key (AK), and it can be called a quote [17] or evidence, which is used to establish trustworthiness through identities. Because of this, the quote encapsulates code identity, ISV identity, TEE identity, and various security attributes, e.g., security version number (SVN) of a TEE [10], associated with a TService instance. A relying party can examine the quote to determine whether the TService is trustworthy or not via verification infrastructure.

The quote is not a secret, and it must ensure its uniqueness, integrity and authenticity (UniqIntAuth). The quote generation involves cryptographically measuring the instantiated TCB, signing the measurements with an AK, including a nonce.

The AtQ accommodates a piece of user-defined information, called Quote User Defined Data (QUDD). The QUDD can provide extra identities specific to a TService. Therefore, the AtQ can in turn help protect the integrity of Attest Header Lines (AHLs) during the handshake phase which we will discuss in section 3.2.

It's worth noting that not all quotes are the same, especially if they are structured by differ-

ent vendors, so a label of quote type should be attached along with AtQ.

2.3 Attest Base (AtB)

AtB is the totality of computing resources serving client request handling, including hardware, firmware, software, and access controls to work together to deliver trustworthy service quality with enforced security/privacy policy. It can also be considered as a group of collaborating TService instances running in their own attestable TEEs respectively, which are capable of proving the integrity of the execution state.

In this paper, the computing resources of TService are offered by AtB to be accessible to the client through a series of trusted transactions. How to attest those trustworthy services is determined by the specified policy in the handshake phase. We suggest using a single TService instance for each AtB to reduce the complexity and attack surface as much as possible.

The AtB, serving for a particular service tied to a Uniform Resource Identifier (URI), should be directly or indirectly attested by a client through HTTPA/2 protocol.

In the case of a AtB formed by multiple TServices instances, an upfront TServices instance takes responsibility for performing local attestation on the rest of TServices instances to establish trustworthy relationships with them. After that, the upfront TServices can selectively collect their quotes for client-side verification during the HTTPA/2 handshake phase.

2.4 Three Types of Request

There are three types of request defined by the HTTPA/2 protocol, including Un-trusted Request (UtR) Attest Request (AtR), and Trusted Request (TrR). UtR is used in HTTP transactions; AtR is used in both transactions of Attest Handshake (AtHS) and Attest Secret Provisioning (AtSP); TrR is used in trusted transaction. For convenience we refer to the AtR and TrR as "HTTPA/2 request".

Regarding HTTP method, we propose a new HTTP method, called "ATTEST", to perform the transactions of AtHS and AtSP. The HTTP request using ATTEST method is called AtR. Regarding HTTP header fields, we propose to augment them with additional ones called Attest Header Fields (AHFs) prefixed with string "Attest-". Without AHFs, it must be a UtR in terms of HTTPA/2.

The AHFs are dedicated to HTTPA traffic. For example, they can be used to authenticate the identity of HTTPA/2 transactions, indicate which AtB to request, convey confidential metadata (see section 2.7), provision secrets, present ticket (see section 2.5), etc.

Last one is AHL, it consists of AHF and its values in a standard form [19]. We use it to signify a single piece of annotated data associated with the current HTTPA/2 request.

2.4.1 Un-trusted Request (UtR)

The UtR is simply an ordinary type of HTTP request, which does not use ATTEST method nor does it contain any AHLs.

Before a UtR reaches a TService, the UtR can be easily eavesdropped on or tampered with along the communication path. Even protected by TLS, it is still possible to be attacked when crossing any application gateway or L7 firewall since those intervening middle-boxes are untrusted and will terminate TLS connections hop by hop [1]. Therefore, there is no guarantee of ConfIntAuth. That's why the TService cannot treat the request as trustworthy, but it is still possible for TService to handle UtR if allowed by the service-side policy. Thus, we don't suggest TService to handle any one of them for the sake of security.

2.4.2 Attest Request (AtR)

The AtR is an HTTP request equipped with both ATTEST method and AHLs for AtHS and AtSP. If any AtR was not successfully handled by corresponding TService, subsequent TrR, described in the section 2.4.3, will no longer be acceptable to this TService. We describe the major difference between an AtR used in AtHS and AtSP respectively as follows:

AtHS The AtR used in AtHS is designed to request all necessary resources for handling both types of AtR used in AtSP and TrR. For example, one of the most important resources is AtB (see section 2.3), which may be scheduled or allocated by a server-side resource arbiter. Typically (but not always), an upfront TService can directly designate itself as the AtB for this client. For the complete explanation in detail, see section 3.2.

In addition, this AtR should not be used to carry any confidential information, because the key material cannot be derived at this moment. TService can encrypt sensitive data in the response message since it has already received the required key share from the client and be able to derive the key material for encryption.

AtSP The AtR of AtSP is optional and may not be present in HTTPA/2 traffic flow since in some cases the TService does not need any AtB-wide secrets provided by the client to work. In the common case, TService needs secret provisioning to configure its working environment, such as connecting to databases, setup signing keys, and certificates, etc. This AtR must be issued after all TEE resources have been allocated through the AtHS transaction described above. It's worth noting that this request is not required to be issued before any TrR 2.4.3. With such flexibility, TService can get extra information or do some operations beforehand through preceding TrRs.

Importantly, this AtR is responsible to provision AtB-wide secrets to AtB, such as key credentials, tokens, passwords, etc. Those secrets will be wrapped by an encryption key derived from the key exchange in the AtHS phase 3.2. Furthermore, the TService must ensure that those provisioned secrets will be eliminated after use, AtB

get released, or any failure occurred in processing AtR. For the complete explanation in detail, see section 3.3.

The two kinds of AtR introduced above are the core of HTTPA/2 protocol. Both of them can be treated as GET request messages to save a RTT, and they can also be used to transmit the protected sensitive data to both sides, except for the AtR of AtHS due to the key exchange not yet completed as noted earlier.

2.4.3 Trusted Request (TrR)

The TrR can be issued right after successful AtHS (see section 2.4.2) where an AtB is allocated. Although, TrR does not use ATTEST method, it should contain AHLs to indicate that it is a TrR not a UtR. In other words, the TrR is nothing but an ordinary HTTP request with some AHLs. Within those AHLs, one of them must be AtB ID to determine which AtB is targeted in addition to the specified URI. With that, the TrR can be dispatched to proper TService to handle this request.

In essence, the TrR is designed to interact with a TService for sensitive data processing. The HTTPA/2 must ensure ConfIntAuth of a set of selected data, which may be distributed within the message body or even in the header or request line, for end-to-end protection. It turns out that not all message bytes would be protected under HTTPA/2 like TLS does. As a result, the HTTPA/2 may not be suitable for certain scenarios, e.g., simply want to encrypt all traffic bytes hop by hop. However, in most cases, the HTTPA/2 can offer a number of obvious benefits without TLS. For example, users do not need to worry about data leakage due to TLS termination, and they can save the resources required by the TLS connections. In some special cases, the HTTPA/2 can be combined with TLS to provide stronger protection but the performance overhead can be significant (see section 2.8).

There are many potential ways to optimize Internet service infrastructure/platform by means of

adopting HTTPA/2 since the insensitive part of HTTPA/2 messages can be used as useful hints to improve the efficiency of message caching or routing/dispatching, risk monitoring, malicious message detection and so on, helping protect sensitive data in motion, as well as in processing by the client-chosen TServices.

2.5 Attest Ticket (AtT)

AtT is a type of AHL used to ensure the integrity and authenticity (IntAuth) of AHLs and freshness by applying AAD to each HTTPA/2 request, except for the AtR of AtHS which is the initiating request for the handshake. AtT is required to be unique for single use so as to mitigate the replay attack as it can be ensured by AAD in practice. Moreover, the AtT should be appended at the very end of the request body as the last trailer [6] because there might be TrC or other trailers which need to be protected by the AtT as well.

Regarding the AtR of AtHS, there is no protection from AtT, because there are no derived keys available to use at such an early stage. In order to protect the AtR of AtHS, we can use either client-side quote or pre-configured signing key methods to ensure the IntAuth instead of AtT. Typically, there are four situations to consider: mHTTPA, client with CA-signed certificate, client with self-signed certificate, and nothing to provide.

Mutual HTTPA (mHTTPA) With mutual HTTPA being used, the client must be running on a TEE as TEE-based client (TClient), which is capable of generating a client-side AtQ. The AtQ can be used to ensure the IntAuth of AtR by means of including the digest of AHLs into its QUDD, and the server-side should have a proper trusted attestation authority to verify it.

This is the recommended approach to build mutual trust between TClient and TService, but the client-side usually lacks of TEE feature support.

Client with CA-signed Certificate In this case, the client signs the AHLs of AtR along with a trusted certificate, and TService should be able to verify the signature with respective CA certificate chain. This way helps TService to identify the user identity.

In addition, the mHTTPA can be enabled at the same time to make it more secure and trustworthy on both sides if possible.

Client with self-signed Certificate In this situation, the client should sign the AHLs of AtR using temporary signing key, and TService should verify the signature using its self-signed certificate enclosed in the same AHL. This approach is not safe since the TService may receive compromised AtR.

Nothing to provide There is no way to protect the integrity of AHLs under these circumstances. We recommend at least using the temporary generated signing key with the corresponding self-signed certificate. It's worth noting that even if the AHLs of AtT is compromised, the client is able to detect the problem by checking the received AtQ of the TService as the QUDD embedded in AtQ will ensure the integrity of AHLs in its request and response messages altogether.

It is difficult for the client to simply use the self-signed certificate to prove its identity, let alone in the case of nothing to provide. Again we recommend the client to combine mHTTPA and CA signed certificate approaches together to establish strong trustworthy relationship between TClient and TService if the server also wants to identify the client's identity at the initiating request, AtR. If it is not the case, the client must detect whether any unexpected changes occurred in the AHLs of AtR as an additional critical step to defend against Man-in-the-Middle (MITM) and downgrade attacks.

2.6 Attest Binder (AtBr)

AtBr is a type of AHL used to ensure the binding between HTTPA/2 request and the corresponding response. The AHL of AtBr should be added into the response message as the last trailer [6]. The AtBr typically holds the Message Authentication Code (MAC) to protect two components: all AHLs of the current response, and the value of AtT in its corresponding request. We can choose other cryptographic algorithms for encryption and message authentication, e.g., Authenticated Associated Data (AAD), Authenticated Encryption with Associated Data (AEAD) [16] to ensure the IntAuth of the AtBr.

The AtBr should present in all HTTPA/2 response messages, except for the response of AtR in the AtHS phase 3.2. The reason is the quote of TService can achieve the same purpose without the help of AtBr.

2.7 Trusted Cargo (TrC)

The TrC can appear in both of HTTPA/2 request and response messages, except for the AtR of AtHS. The TrC serves as a vehicle to carry confidential information which needs to be protected by authenticated encryption.

TrC can be used to protect some sensitive metadata such as data type, location, size, and key index to tell the places in which the ciphertext or signed plaintext is located in the message body. The key index indicates which key should be used to decrypt those encrypted messages or verify the message's integrity. Potentially, there is much useful metadata that can be included in TrC, but we should keep it minimum as size limits might be enforced by intermediaries in the network path.

The way to structure the metadata and how to parse it is not defined by this paper. We leave it to the future extensions of HTTPA/2 or it can be customized by application.

Finally, the TrC should be put in a trailer [6] since its variable length affects the position information it contains. Again, the value of TrC must be protected from eavesdropping on or ma-

nipulating by the means of AE.

2.8 Trusted Transport Layer Security (TrTLS)

HTTPA/2 protects the selected parts of an HTTP message. If users want to protect the entire HTTP message—every bit of the message, TLS can leverage HTTPA/2 to establish a secure connection at L5 between the client and its adjacent middlebox, which we call TrTLS. The TrTLS makes use of AtHS to transmit HELLO messages of TLS [21] to the client and TService respectively for handshake. This way can make the initial handshake of the secure transport layer protocol trustworthy. We consider three cases of endpoints as follows:

TClient In the case of TClient endpoint, the TClient leverages its QUDD to ensure the IntAuth of the client hello message to establish TLS connection. The server-side verifier helps verify the QUDD. If the attestation is successful, the trusted endpoint of TClient will be established as TrTLS. Note that the TrTLS module should be co-located in the same TEE with TClient.

Frontend TService The frontend TService is defined as a TService which can communicate with the client without any L7 middleboxes in between. In other words, the communication between the TService and the client has no TLS terminators. This implies that TService can establish a secure transport layer connection directly with its client. Thus, the IntAuth of the server-side HELLO message can be fully protected by the QUDD of TService in a similar way described in the above case of TClient but in the reverse direction.

Backend TService In the case of a backend TService endpoint, the connection of the secure transport layer will be terminated by at least one middle-box e.g., application gateway, reverse

proxy, or L7 load balancer. Although TService has no direct connection with its client, the trusted connection of TLS between the client and the first middlebox can be established by checking the results of RA from the backend TService. The middlebox needs to consider the mapping of the request and the response with the backend TService to be correct in order to decide whether to use the results of RA to build a trusted connection or not. Admittedly, this is the least trustworthy configuration in terms of full traffic encryption when it is compared with the two cases mentioned above because the attack surface includes those vulnerable middleboxes in the TrTLS connection.

After the initial message is exchanged through AtHS, the encrypted channel can be established under the HTTPA/2 at L5, so the following traffic will be encrypted and inherit the attested assurances of the TEE from HTTPA/2. In the case of the ordinary TLS connection prior to HTTPA/2, the TrTLS mechanism can disconnect the already built TLS connection and then re-establish a trustworthy TLS connection seamlessly. We simply present the high-level concept of TrTLS in this paper and may discuss more details in another paper.

3 Protocol Transactions

In this section, we provide detailed definitions of all HTTPA/2 transactions.

3.1 Preflight Check Phase

The preflight request gives the Web service a chance to see what the actual AtR looks like before it is made, so the service can decide whether it is acceptable or not. In addition, the client endpoint performs the preflight check as a security measure to ensure that the visiting service can understand the ATTEST method, AHFs, and its implied security assurance.

To start with HTTPA/2, a preflight request could be issued by a client as optional to check

whether the Web service, specified by URI in the request line, is TEE-aware and prepare for AtHS. In the case that the client is a Web browser, the preflight request can be automatically issued when the AtR qualifies as "to be preflighted".

The reason we need the preflight transaction is that it is a lightweight HTTP OPTIONS [7] request, which will not consume a lot of computing resources to handle, compared to the AtR. Caching the preflight result can avoid the re-check operation during a specified time window.

Passing this check does not guarantee that the AtR can be successfully handled by this service. For example, the TService may run out of resources, or the client's cipher suites are not supported, and so on.

The preflight is an idempotent operation, e.g., there is no additional effect if it is called more than once with the same input parameters. The client can also use the preflight to detect the capabilities of AtB 2.3, without implying any real actions.

As shown in Figure.1, an OPTIONS request should be honored by an HTTPA/2 compliant TService. In the preflight transaction, it has standard HFs to specify the method and AHLs which will be sent out later to the same TService if they are acceptable. Those HFs are described respectively as follows:

1. HFs in request message

- (a) Access-Control-Request-Method This HF carries a list of methods indicating that ATTEST method will be used in the next request if the service can support it.
- (b) Access-Control-Request-Headers This HF carries a list of field names indicating that the AHFs will be included in the next request if the service can support it.

2. HFs in response message

(a) Allow

This HF carries a list of supported methods by the visiting service. It must contain the ATTEST method for the client to proceed with AtR; otherwise, the AtR is not acceptable by this service and will be denied if received it.

- (b) Access-Control-Allow-Headers
 This HF carries a list of allowed AHFs.
 The client needs to check that all of the requested AHFs should be contained in this resulting field.
- (c) Access-Control-Max-Age
 This HF indicates how long the preflight check results can be cached.

3.2 Attest Handshake (AtHS) Phase

The AtHS phase contains a core transaction of HTTPA/2. In a single round trip time (one RTT), the AtR and its response accomplishes three major tasks, including key exchange, AtB allocation and AtQ exchange, as shown in Figure.2:

1. Key Exchange

It is necessary to complete the key exchange process before any sensitive information can be transmitted between the client and TService. The exact steps within this will vary depending upon the kind of key exchange algorithm used and the cipher suites supported by both sides.

In HTTPA/2, the key exchange process follows TLS 1.3 [21] and recommends a set of key exchange methods to meet evolving needs for stronger security.

Insecure cipher suites have been excluded, and all public-key-based key exchange mechanisms now provide Perfect Forward Secrecy (PFS), e.g., Ephemeral Elliptic Curve Diffie-Hellman (ECDHE). Note that it is mandatory that the fresh ephemeral keys are generated and used, and destroyed afterward [18] inside the TEE of TService.

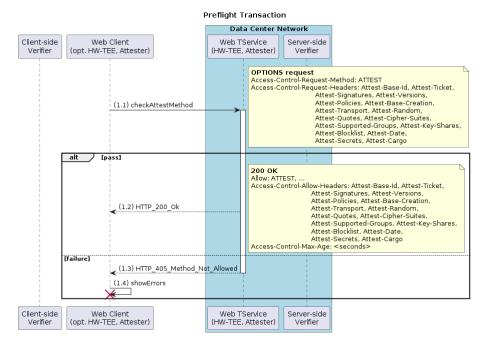


Figure 1: Preflight transaction

When the key exchange is completed, we recommend using HMAC-based Extract-and-Expand Key Derivation Function (HKDF) [13] as an underlying primitive for key derivation.

We describe the key negotiation between the client and the TService in terms of AHFs set in request and response respectively as follows:

- (a) AHFs in request message (or AtR):
 - i. Attest-Cipher-Suites
 It is a list of cipher suites that indicates the AEAD algorithm/HKDF hash pairs supported by the client.
 - ii. Attest-Supported-Groups
 It is a list of named groups [15]
 that indicates the (EC)DHE
 groups supported by the client
 for key exchange, ordered from
 most preferred to least preferred.
 The AHL of Attest-Key-Shares

contains corresponding (EC)DHE key shares e.g., pubkeys for some or all of these groups.

iii. Attest-Key-Shares

Its value contains a list of the client's cryptographic parameters for possible supported groups indicated in the AHL of Attest-Supported-Groups for negotiation. We can refer to the corresponding data structure described in TLS 1.3 [21]. It is a time-consuming operation to generate those parameters (see 3.1 in Figure.2)

iv. Attest-Random

It is 32 bytes of a random nonce, which is used to derive the master secret and other key materials by TService. The purpose of the random nonce is to bind the master secret and the keys to this particular handshake. This way mitigates

Attestation Handshake Transaction Data Center Network Client-side Server-side Verifier Web Client Web TService Verifier (opt. HW-TEE, Attester) (HW-TEE, Attester) (3.1) genExchangeKeys [For mutual attestation] opt (3.2) genQuotes ATTEST request ATTEST request Attest-Versions: <ure><ur>Attest-VersionsAttest-Date: <GMT>Attest-Date: <GMT>Attest-Policies: <security policies>Attest-Base-Creation: <methed>Attest-Random:
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Figure 2: Attest handshake (AtHS) transaction

Verifier

the replay attack to the handshake as long as each peer properly generates this random nonce.

(b) AHFs in response message

i. Attest-Cipher-Suite

It indicates the selected cipher suites, i.e. a symmetric cipher/HKDF hash pair for HTTPA/2 message protection.

ii. Attest-Supported-Group It indicates the selected named group to exchange ECDHE key share generated by the TService.

iii. Attest-Key-Share

Its value contains the TService's cryptographic parameters accordingly (see 3.7 in Figure.2).

iv. Attest-Random

It takes the same mechanism as the Attest-Random in the request. Instead, it is used by the client to derive the master secret and other key materials.

This handshake establishes one or more input secrets combined to create the actual keying materials. The key derivation process (see 3.9, 3.15 in Figure.2), which makes use of HKDF, incorporates both the input secrets and the AHLs of handshake. Note that anyone can observe this handshake process if it is not protected by the byte-to-byte encryption at L5, but it is safe since the secrets of the key exchange process will never be sent over the wire.

2. AtB Allocation

This task takes care of resource allocation. The upfront TService needs to prepare essential resources before assigning an unique AtB identifier to the AtB, which is used by the client to ask TService to process its sensitive data on this AtB (see 3.6 in Figure.2).

(a) AHFs in request message or AtR:

i. Attest-Policies

It can contain various types of security policies, which can be selectively supported by this AtB of TService. There are two aspects to consider as follows:

Instances attestation

direct: all instances should be verified by the client.
indirect: only the contact instance should be verified by the client remotely.

Un-trusted requests

allowUntrustedReq: it allows UtR to be handled by the TService on this AtB (disabled by default).

ii. Attest-Base-Creation

It specifies a method used for the creation of AtB. There might be several options available to select:

new

It means that the AtB should be newly created for the client to use. If the contact TService is a new one, then it can be assigned to this client immediately.

reuse

This option allows reusable AtB to be used by this client, but the AtB should ensure that all traces associated with the previous client are erased. So far, there is no such TEE, which can achieve this security feature strictly, and we cannot fully rely on software to emulate it. As a result, the client should evaluate the risks before specifying this option.

shared

A shareable AtB can be allocated to this client. The client does not care whether it is a

clean base or not. Use it with caution.

iii. Attest-Blocklist

It indicates a list of blocked identities and other types of identifiers, which allows TService to filter out unqualified AtB beforehand. This feature is used to optimize the performance of AtB allocation, as it is quite expensive and inefficient to rely only on the client to collect a set of TService instances by using the trial and error method.

(b) AHFs in response message:

i. Attest-Base-ID

This identifier signifies the allocated AtB, which has been tied to this particular client who sent the AtHS request. It should be used in subsequent HTTPA/2 requests to ensure those requests can be efficiently dispatched into TServices. Given that the HTTPA/2 request dispatcher may not be trustworthy, and won't be capable to check its integrity of it. As a result, it cannot guarantee that those requests could be delivered into their matched AtBs. To remedy this problem, the dispatcher should be capable to identify invalid AtB ID as possible, and the receiving TService should validate it right after integrity check (see 4.2 in Figure.3, 5.2 in Figure.4).

Note that the max-age directive set here indicates how long this AtB could be kept alive on the server side.

3. AtO Exchange

In HTTPA/2, a successful RA [2] increases client's confidence by assuring the targeting services running inside a curated and trustworthy AtB. The client can also determine the level of trust in the security assurances

provided by TServices through AtB.

The RA is mainly aimed to provision secrets to a TEE, In this solution, we leverage this mechanism to set it as the root trust of the HTTPA/2 transactions instead of certificate-based trust, e.g., TLS. To facilitate it, we integrate the RA with the key exchange mechanism above to perform a handshake, which passes the assurance to derived ephemeral key materials (see 3.9 in Figure.2). Those keys can be in turn used to wrap secrets and sensitive data designated by the client or TService in either direction. During RA process, the AtQ (see section 2.2) plays a key role to attest TService. It provides evidence (quote) to prove authenticity of the relevant TService (see 3.8 in Figure.2). The client can just rely on it to decide whether the TService is a trustworthy peer or not [4].

To appraise AtQ, we need a trusted authority to be the verifier to perform the process of AtQ verification, and reports issues on this AtQ, e.g., TCB issues (see 3.12 in Figure.2). The result of verification produced by the verifier should be further assessed by the client according to its pre-configured policy rules and applied security contexts. Importantly, the TService should ensure the integrity and authenticity of all AHLs of AtR and its response through the QUDD of AtQ, and vice versa in case of mHTTPA/2. The following AHFs should be supported by HTTPA/2 protocol for RA.

(a) AHFs in request message (or AtR):

i. Attest-Quotes

It can only appear in mHTTPA/2 mode to indicate a set of AtQs generated from the TClients for targeting TService to verify. (see 3.2, 3.3, 3.4, 3.5 in Figure.2). These quotes should be used to ensure IntAuth of the AHLs of this AtR through their QUDD.

Note that the max-age directive

indicates when these quotes are outdated and its cached verification results should be cleared up from AtB to avoid broken assurance. In addition, all client-side quotes must be verified by server-side verifier and validated by TServices before a AtB ID can be issued.

(b) AHFs in response message

i. Attest-Quotes

It is mandatory for a AtB to present its AtQs to the client for client-side verification. The IntAuth of both AHLs of the AtR and its response should be ensured by its QUDDs to protect the transaction completely.

The client must verify the AtQ to authenticate its identities of remote AtB (see 3.8, 3.10, 3.11, 3.12 in Figure.2). The client should not trust anything received from TService before AtQs is successfully verified and evaluated. Whether the integrity of AHLs is held should be determined by client-side security policies. Note that the TService quotes can be selectively encrypted in its parts through TrC to hide its identity information.

There are several remaining AHFs, which are important to this transaction as they provide other necessary information and useful security properties:

(a) AHFs in request message

i. Attest-Versions

The client presents an ordered list of supported versions of HTTPA to negotiate with its targeting TService.

ii. Attest-Date

It is the Coordinated Universal

Time (UTC) when client initiates a AtHS.

iii. Attest-Signatures

It contains a set of signatures, which are used to ensure IntAuth of AHLs in this AtR through client-side signing key (see section 2.5).

iv. Attest-Transport

As described in section 2.8, the client HELLO message should be put in here. With this, the TService can enforce a trustworthy and secure connection at L5, which is a bit similar to what HTTP Strict Transport Security (HSTS) does [9].

(b) AHFs in response message

i. Attest-Version

It shows client which version of HTTPA is selected by TService to support.

ii. Attest-Transport

Similarly, the TService returns its HELLO message to the client for a secure transport layer handshake.

iii. Attest-Expires

It indicates when the allocated AtB will go expire and its related resources will get released. It provides another layer of security to reduce the chance of this AtB being attacked.

iv. Attest-Secrets

It is an ordered list of AtB-wide secrets, which are provisioned by TService if client expects them. This way can save a RTT of AtSP (see section 3.3) in case of TService won't demand secrets from client immediately.

v. Attest-Cargo

The usage of this field is described in section 2.7. Note that "Attest-Cargo" is a AHF while TrC is the corresponding content which plays an important role on sensitive data encryption and authentication.

Apart from those tasks above, this AtR can act as a GET request, but it cannot be trusted due to incomplete key exchange at this moment, which means it cannot contains any sensitive data, but its response can be trusted as the key exchange process completed at TService-side, and before it gets returned. Therefore, the TService-side sensitive data can be safely transmitted back to the client through the TrC.

3.3 Attest Secret Provisioning (AtSP) Phase

As mentioned in section 3, the main purpose of AtSP is to securely deliver secrets to a trustworthy AtB, which has been verified by a server-side verifier. The AtR of AtSP is intended to be used for this purpose. To be precise, it is for AtB-wide and client-wide secret provisioning. On the contrary, the request-wide or response-wide secrets should be carried by the TrCs (see section 2.7) of HTTPA/2 transactions. In addition, the failure of AtSP will causes AtB termination immediately.

As shown in Figure.3, the AtSP transaction can be used to provision secrets in two directions since the AtB and its key materials already got derived through AtHS (see section 3.2) on both sides; thus, the AHLs can be fully protected during this phase. Moreover, AtR of AtSP can be issued by the client any number of times at anytime after AtHS.

These AHLs described in following:

1. AHFs in request message (or AtR)

(a) Attest-Base-ID

This identifier is used to specify which AtB is targeted to handle this AtR of AtSP. With this ID, the TService can firstly validate it against its serving list to make sure correctly handling of this request (see 4.2 in Figure.3). However, the TService should quietly ignore it if the ID is not valid for its residing AtB as the receiving TService should not expose any information for an adversary to exploit.

(b) Attest-Ticket

The usage of this field is explained in section 2.5. The value of this field must be unique to prevent a replay attack. Also, it ensures the IntAuth of the AHLs in this request.

(c) Attest-Secrets

It contains an ordered list of secrets, which is wrapped up by means of AE as a standard way for strong protection. Moreover, each secret should be able to be referred to by the client later using the index. For example, specifying a provisioned secret that is used to decrypt embedded sensitive data. Again, the receiving AtB should be terminated if any of these provisioned secrets cannot be validated or accepted by the AtB (see 4.3 in Figure.3).

(d) Attest-Cargo

This field is optional, it can be used to carry any sensitive information, which is meaningful to TService (see section 2.7). Note that this paper is not intended to define the structure of its content, which could be addressed in another one.

2. AHFs in response message:

(a) Attest-Binder

It is used to make sure the request to response is binding together to identify this transaction uniquely (see section 2.6).

(b) Attest-Secrets

In this HF, these contained wrapped secrets will be provisioned back to the client. As noted earlier, this can be

Secret Provisioning Transaction

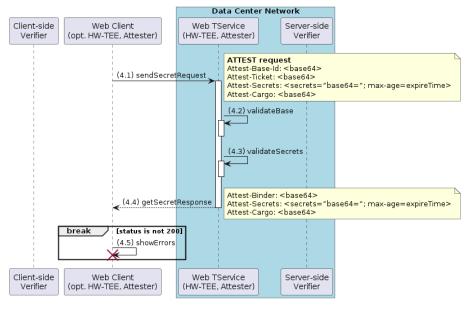


Figure 3: Attest secret provisioning (AtSP) transaction

merged into the response AHLs in AtR of AtHS (see section 3.2).

(c) Attest-Cargo Similarly, it can be used to carry sensitive information/data back to the client (see section 2.7).

3.4 Trusted Communication Phase

When AtB is allocated for the client, it can subsequently issue TrR (see section 2.4.3) to do the real work. Basically, the TrR is an ordinary HTTP request with some extra AHLs, which are described in detail as follows:

1. AHFs in request message:

(a) Attest-Base-ID

It specifies which AtB to handle this request, and should be validated by targeting TService (see 5.2 in Figure.4) before processing this request (see 5.3 in Figure.4).

(b) Attest-Ticket

This field has been explained above (see section 2.5), which is intended to authenticate this request, and prevent other AHLs from being tampered with or being replayed.

(c) Attest-Cargo

As noted earlier, this field is optional, and the client can use it to transfer arbitrary sensitive information to TService (see section 2.7).

(d) Attest-Base-Termination

We can include this AHF if it is the last TrR towards the AtB. It is recommended way to terminate a AtB actively.

The termination method can be one of the following options:

cleanup

This means that the terminated AtB can be reused by other clients.

destroy

Trusted Transaction

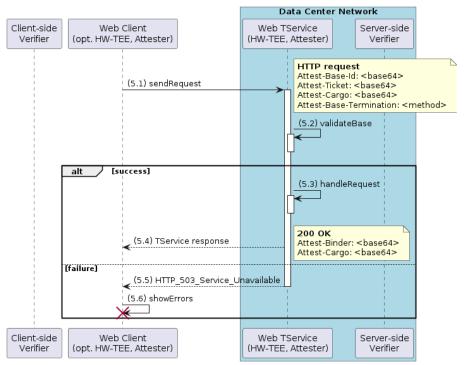


Figure 4: Trusted transaction

Specify this method, if the AtB should not be reused or shared by any other clients.

keep

This allows AtB to be shared with other clients. Be careful, this method is less safe as the residual data could be exploited and leaked to the next client if any.

2. AHFs in response message:

(a) Attest-Binder

As explained earlier, the HTTPA/2 uses it to ensure the IntAuth of both request and response together (see section 2.6).

(b) Attest-Cargo

As noted earlier, the TService can leverage this mechanism to transfer arbitrary sensitive information back to its client (see section 2.7).

3.5 Protocol Flow

As shown in Figure.5, we illustrate those transactions from client perspective, including preflight, AtHS, AtSP, and trusted request in a workflow diagram. In the design of HTTPA/2, only the phase of AtHS is required, which not only largely simplifies the interaction between the client and the TService but also improves the user experience (UX).

Figure.6 shows the workflow, which can help understand how those transactions are distinguished in TService.

4 Security Considerations

In this section, we discuss security properties and the potential vulnerabilities, as is necessary for understanding HTTPA/2.

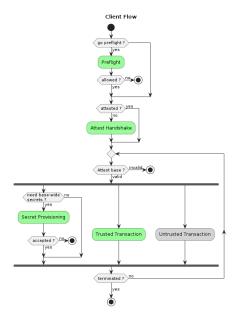


Figure 5: HTTPA transaction workflow from the client view.

4.1 Layer 7 End-to-End Protection

In cloud computing scenarios, intermediary nodes, such as L7 load balancer or reverse proxy, are used commonly to improve the network performance to deliver the best web experience. However, the great web experience does not come for free. The secure communication based on TLS only protects transmitted data hop-byhop at layer 5 (L5). The intermediary nodes may need TLS termination to inspect HTTP messages in plain text for better network performance. As a consequence, the intermediary nodes can read and modify any HTTP information at L7. Although TLS itself is not the problem, it cannot protect sensitive information above L5 where most Web services are located. That is the gap between L5 and L7 that causes the underlying vulnerability. Therefore, the trust model including intermediary nodes, which are over L5, is problematic [23], because, in reality, intermediary nodes are not necessar-

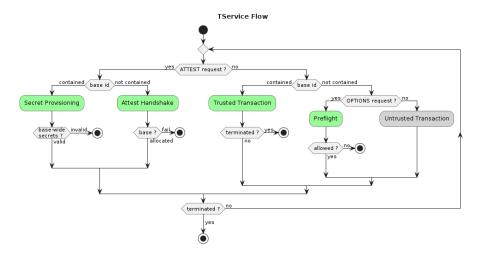


Figure 6: HTTPA transaction workflow from the TService view

ily trustworthy. Intermediary nodes may leak the privacy and manipulate the header lines of HTTP message. Even in the case, where intermediaries are fully trusted, an attacker may exploit the vulnerability of the hop-by-hop architecture and lead to data breaches. HTTPA/2 helps protect AHLs and the sensitive information of HTTP message end-to-end at L7. long as the protection does not encrypt the necessary information against proxy operations [23], HTTPA/2 can provide guarantees that the protected message can survive across middleboxes to reach the endpoint. Especially, HTTPA/2 provides an encryption mechanism at the level of HTTP message, where only the selected information, some header lines or payloads, is encrypted rather than the entire message. Thus, the parts of HTTPA information without protection may be exploited to spoof or manipulate. If we want to protect every bit of HTTPA message hop-by-hop, TLS is highly recommended in combine with HTTPA/2 for use.

In the implementation, the TServices can make a privacy policy to determine to what degree the HTTPA message is protected to the L7 endpoint without TLS for better network performance. If the message is highly sensitive entirely,

TLS can come to help in addition, but only up to the security of the L5 hop point.

4.2 Replay Protection

A replay attack should be considered in terms of design and implementation. To mitigate replay attacks, most AEAD algorithms require a unique nonce for each message. In AtR, random numbers are used. In TrR, a sequential nonce is used on either endpoint accordingly. Assuming strictly increasing numbers in sequence, the replay attack can be easily detected if any received number is duplicated or no larger than the previously received number. For reliable transport, the policy can be made to accept only TrR with a nonce that is equal to the previous number plus one.

4.3 Downgrade Protection

The cryptographic parameters of configuration should be the same for both parties as if there is no presence of an attacker between them. We should always negotiate the preferred common parameters with the peer. If the negotiated parameters of configuration are different for both parties, it could make peers use a weaker cryptographic mode than the one they should use, thus leading to a potential downgrade attack [3]. In HTTPA/2, TService uses AtQ to authenticate its identity and the integrity of the AtHS to the client. In mHTTPA/2, the client uses AtQ carried by AtR for proving its own authenticity and the message integrity. Thus, the communication traffic of the handshake across intermediaries cannot be compromised by attackers.

4.4 Privacy Considerations

Privacy threats are considerably reduced by means of HTTPA/2 across intermediary nodes. End-to-end access restriction of integrity and encryption on the HTTPA/2 AHLs and payloads, which are not used to block proxy operations, aids in mitigating attacks to the communication between the client and the TService. On the other hand, the unprotected part of HTTP headers and payloads, which is also intended to be, may reveal information related to the sensitive and protected parts. Then privacy may be leaked. For example, the HTTP message fields visible to on-path entities are only used for the purpose of transporting the message to the endpoint, whereas the AHLs and its binding payloads are encrypted or signed. It is possible for attackers to exploit the visible parts of HTTP messages to infer the encrypted information if the privacy-preserving policy is not well set up. Unprotected error messages can reveal information about the security state in the communication between the endpoints. Unprotected signaling messages can reveal information about reliable transport.

The length of HTTPA/2 message fields can reveal information about the message. TService may use a padding scheme to protect against traffic analysis. After all, HTTPA/2 provides a new dimension for applications to further protect privacy.

4.5 Roots of Trust (RoT)

Many security mechanisms are currently rooted in software; however, we have to trust underlying components, including software, firmware, and hardware. A vulnerability of the components could be easily exploited to compromise the security mechanisms when the RoT is broken. One way to reduce that risk of vulnerability is to choose highly reliable RoT. RoT consists of trusted hardware, firmware, and software components that perform specific, critical security functions [22]. RoT is supposed to be trusted and more secure, so it is usually used to provide strong assurances for the desired security properties. In HTTPA/2, the inherent RoT is the AtB or TEEs, which provide a firm foundation to build security and trust. With AtB being used in HTTPA/2, we believe that the risks to security and privacy can be greatly reduced.

5 Conclusion

In this paper, we propose the HTTPA/2 protocol, a major revision of HTTPA/1. HTTPA/2 is a layer 7 protocol that builds trusted end-to-end communication between Hypertext Transfer Protocol (HTTP) endpoints. An integral part of HTTPA/2 is based on confidential computing, e.g., TEE, which is used to build verifiable trust between endpoints with remote attestation. Communication between trusted endpoints is better protected across intermediary nodes which may not have TLS protection. This protection helps prevent HTTPA/2 metadata and the selected HTTP data from being compromised by internal attackers, even with TLS termination.

In addition to security advantage, the HTTPA/2 also illustrates the performance advantages over HTTPA/1, as it is not mandatory to enforce TLS; hence the overheads of TLS can be saved. Furthermore, HTTPA/2 provides flexibility for a service provider to decide which part of the HTTP message is required to be

protected. This feature can potentially be leveraged by CSPs to optimize their networking configuration and service deployment to improve the throughput and response time. With those improvements, the energy of electricity can be saved as well.

6 Future Work

To further realize HTTPA/2 in the real world, we will be focused on proof-of-concept (PoC) to demonstrate its validness and soundness. We will apply the PoC codes of HTTPA/2 to various use cases in practice. Lastly, we plan to release a reference implementation towards generalization to open source.

In the future, we expect emerging private AI applications to leverage HTTPA/2 to deliver its end-to-end trusted service for processing sensitive data and protecting model IP. HTTPA/2 will enable Trust-as-a-Service (TaaS) for more trustworthy Internet. With HTTPA/2 and TaaS, Internet users will have freedom of choice to trust, the right to verify assurances, and the right to know the verified details. Users are able to make their decision out of free will based on the faithful results that they consider and choose to believe. It becomes possible that we can build genuine trust between two endpoints. Thus, we believe that HTTPA/2 will accelerate the transformation process towards trustworthy Internet for a better digital world.

7 Acknowledgements

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8 Notices & Disclaimers

No product or component can be absolutely secure.

Acronyms

(EC)DHE Ephemeral (Elliptic Curve) Diffie-Hellman. 9

AAD Authenticated Associated Data. 5, 6

AE Authenticated Encryption. 7, 14

AEAD Authenticated Encryption with Associated Data. 6, 9

AHF Attest Header Field. 4, 7–9, 11–15, 17

AHL Attest Header Line. 3–6, 8, 9, 11–15, 18, 19

AK attestation key. 3

AtB Attest Base. 3–5, 8, 11–15, 17, 19

AtBr Attest Binder. 6

AtHS Attest Handshake. 3–8, 10, 12–15, 17, 19

AtQ Attest Quote. 3, 5, 6, 8, 12, 13, 19

AtR Attest Request. 3-9, 11-15, 18, 19

AtSP Attest Secret Provisioning. 3, 4, 13–15, 17

AtT Attest Ticket. 5, 6

CA certification authority. 5, 6

ConfIntAuth confidentiality, integrity and authenticity. 2, 4, 5

CSP Cloud Service Provider. 2, 20

ECDHE Ephemeral Elliptic Curve Diffie-Hellman. 8, 11

HF Header Field. 8, 14

HKDF HMAC-based Extract-and-Expand Key Derivation Function. 9, 11 **HSTS** HTTP Strict Transport Security. 13

HTTP Hypertext Transfer Protocol. 1–5, 8, 15, 18, 19

HTTPA HTTP Attestable. 1–8, 11–14, 17–20

HTTPS HTTP Secure. 2

IntAuth integrity and authenticity. 5–7, 12–14, 17

Intel® SGX Intel® Software Guard Extensions. 3

Intel® TDX Intel® Trust Domain Extensions. 3

ISV independent software vendor. 3

MAC Message Authentication Code. 6

mHTTPA Mutual HTTPA. 5, 6, 12, 19

MITM Man-in-the-Middle. 6

PFS Perfect Forward Secrecy. 8

PII Personally Identifiable Information. 2

PoC proof-of-concept. 20

QService Quoting Service. 3

QUDD Quote User Defined Data. 3, 5–7, 12, 13

RA remote attestation. 1–3, 7, 12

REE Rich Execution Environment. 2

RoT Root of Trust. 19

RTT round trip time. 5, 8, 13

SVN security version number. 3

TaaS Trust-as-a-Service. 20

TCB trusted computing base. 1–3, 12

TClient TEE-based client. 5–7, 12

TEE Trusted Execution Environment. 1–5, 7, 8, 11, 12, 19

TLS Transport Layer Security. 1, 2, 4, 5, 7–9, 12, 17–19

TrC Trusted Cargo. 5, 6, 13, 14

TrR Trusted Request. 3-5, 15, 18

TrTLS Trusted Transport Layer Security. 7

TService TEE-based service. 1–9, 11–15, 17–19

UniqIntAuth uniqueness, integrity and authenticity. 3

URI Uniform Resource Identifier. 3, 5, 8

UTC Coordinated Universal Time. 13

UtR Un-trusted Request. 3-5, 11

UX user experience. 17

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