Hindawi Publishing Corporation
EURASIP Journal on Wireless Communications and Networking
Volume 2006, Article ID 85495, Pages 1–14
DOI 10.1155/WCN/2006/85495

Multiple-Channel Security Architecture and Its Implementation over SSL

Yong Song, Konstantin Beznosov, and Victor C. M. Leung

Department of Electrical and Computer Engineering, Faculty of Applied Sciences, University of British Columbia, 2356 Main Mall, Vancouver, BC, Canada V6T 1Z4

Received 2 October 2005; Revised 18 April 2006; Accepted 21 April 2006

This paper presents multiple-channel SSL (MC-SSL), an architecture and protocol for protecting client-server communications. In contrast to SSL, which provides a single end-to-end secure channel, MC-SSL enables applications to employ multiple channels, each with its own cipher suite and data-flow direction. Our approach also allows for several partially trusted application proxies. The main advantages of MC-SSL over SSL are (a) support for end-to-end security in the presence of partially trusted proxies, and (b) selective data protection for achieving computational efficiency important to resource-constrained clients and heavily loaded servers.

1. INTRODUCTION

While the Internet is advancing from wireline to wireless networks, a growing number of handheld devices—such as cellular phones, PDAs, and palmtops—can access Internet applications, for example, Web, e-mail, multimedia, and so forth. Securing client-server communication between resource-constrained handheld devices and heavily loaded Internet servers has been a challenge. A handheld device has many more constraints than an ordinary computer in terms of power, processor, memory, display, and other resources. The access channels of handheld devices range from 2 G/2.5 G/3 G cellular networks, wireless LAN, and bluetooth to dial-up and LAN. Some of these are slow, unreliable, and expensive. A handheld device is still resource-constrained, even though it uses a wireline interface such as LAN for communication. Besides, the operating system and software of a handheld device often have fewer functions than those of an ordinary computer. However, many Internet applications and protocols are designed mainly for ordinary computers. For these reasons, handheld devices pose challenges to secure client-server communications.

This paper presents a new security architecture and protocol for securing client-server communications, named multiple-channel SSL (MC-SSL). Although this work focuses on wireless handheld or mobile devices, MC-SSL is designed as a general security protocol for a wide range of client-server applications. It supports multiple channels between a client and a server. Each channel can be either a direct or a proxy channel with one or more intermediary proxies; moreover, each channel can have its own cipher suite and data-flow direction. During an application session, a client and a server establish channels according to their specific needs for data protection and selectively use the channels to communicate directly or through proxies.

Compared to secure socket layer/transport layer security (SSL/TLS, or SSL for short) [1], the de facto security protocol for the Web and MC-SSL enjoys four main advantages. First, it enhances end-to-end security in the presence of partially trusted application proxies. Second, with MC-SSL's support for multiple cipher suites, both client and server can optimize computational and communication costs while exchanging data with different protection requirements. Third, it supports channel-direction restriction, which prevents a response channel from being turned into a request channel, and vice versa, by a malicious proxy. Finally, MC-SSL supports channel negotiation based on security policies, device capabilities, and security requirements for the data sent over the channels. Consequently, MC-SSL can better fulfill the diverse requirements of different clients, servers, applications, and users. MC-SSL design extends SSL by introducing new features that enable the SSL protocol and implementations to be reused.

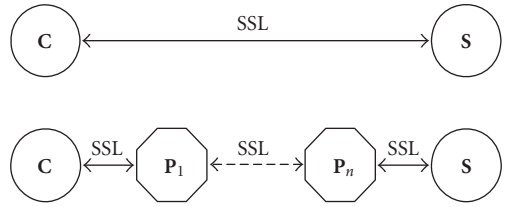


Figure 1: The point-to-point and proxy-chain models of SSL.

The rest of this paper is organized as follows: Section 2 describes the problems and limitations of SSL. Section 3 outlines related work. Section 4 presents the MC-SSL architecture. Section 5 discusses the MC-SSL protocol design. Section 6 demonstrates implementation. Section 7 draws conclusions.

2. PROBLEM MOTIVATION

Although SSL is the de facto application security protocol for the Internet, it has several limitations. First, SSL cannot help applications protect information from partially trusted application proxies, which leads to the necessity of unconditionally trusting proxies. Second, due to the high cost of changing a cipher suite once an SSL connection is established, all data, independent of differences in security requirements, is protected unvaryingly, resulting in either overprotection or underprotection. Third, SSL does not contain sufficient negotiation capabilities to support selective protection of data and the negotiation of proxy use. After a brief description of SSL, this section discusses these limitations in detail.

Figure 1 illustrates a simplified communication model of SSL. The upper part of the figure shows a point-to-point secure channel over a TCP connection between client **C** and server **S**. Channel security is achieved by making use of a cipher suite, which defines a key exchange algorithm, a bulk encryption algorithm, and a hash algorithm. For example, TLS_RSA_WITH_IDEA_CBC_SHA cipher suite uses RSA algorithm [2, 3] to perform authentication and key exchange, IDEA (international data encryption algorithm) [2, 3] to perform encryption and decryption, and SHA-1 (secure hash algorithm) [2, 3] to generate MAC (message authentication code) [1]. MAC protects data integrity. CBC (cipher block chaining) [2, 3] is a mode of operation for block ciphers such as IDEA. Please refer to RFC 2246 [1] for the details of SSL/TLS. The following subsections use the above model to explain the limitations of SSL addressed by MC-SSL.

2.1. Problem with trusted proxies

Application proxies pose security risks. Due to their constraints, many handheld devices require application proxies to perform content transformation or scanning. For example, most Web sites do not provide Web pages designed for handheld devices, and so the Web browser of a handheld device is likely unable to display a Web page not transformed by an intermediary proxy. Even desktop computers sometimes use n application proxies, for example, an application firewall for virus scanning/filtering.

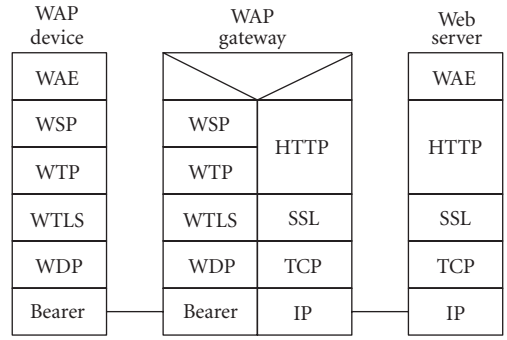


Figure 2: WAP 1.X gateway architecture (adapted from [4]).

The need for an application proxy is not in itself a limitation, but for sensitive information in transit, it becomes difficult to achieve end-to-end security between a client and a server. Although SSL is the de facto security protocol on the Web, it cannot prevent information leakage, tampering, and impersonation by an application proxy.

As illustrated in the lower part of Figure 1, SSL enables point-to-point protection of the communication between any two directly connected entities through unconditionally trusted proxies. SSL is vulnerable to malicious proxies, as any proxy in the chain can read and/or modify data. In other words, a proxy can compromise the end-to-end security between **C** and **S**. The use of proxies with SSL implicitly requires that at least one endpoint (**C** or **S**) has unconditional trust in the proxies used between the endpoints. This requirement can be satisfied only if the proxies are administered by the organization or individual that also administers the trusting endpoint. Note that if a proxy works below the application layer, for example, at the transport layer, then **C** and **S** can still establish an end-to-end SSL session. For this reason, SOCKS proxy mechanism and network address translation (NAT) do not affect the normal operation of SSL. In this paper, the term "proxy" designates a proxy or gateway at the application layer.

A typical example of using proxies with SSL is the WAP 1.X gateway architecture shown in Figure 2. The communication between a WAP device and a WAP gateway is protected by WTLS, a variant of the SSL protocol for wireless communications. Clearly, the WAP 1.X gateway shown in Figure 2 is an application proxy because it performs content transformation, recoding, and/or compression for the content carried by HTTP or WSP/WTP protocols. Since this architecture is a proxy architecture that employs SSL, it has the same limitation as the SSL proxy chains. The architecture is secure only when the gateway is trustworthy, for instance, when the Web server owner provides the gateway.

2.2. Limitation of cipher suites and channel direction

The second limitation of SSL stems from the redundant cryptographic protection in client-server SSL communications.

Cryptographic algorithms such as RSA [2], 3DES [2], and AES are computationally expensive, especially for a handheld device or a heavily loaded server. If a processor is fully dedicated to security processing, the processing requirements for 3DES, AES, SHA (secure hash algorithm) [2], and MD5 (message digest 5) [2] at 10 Mbps are 535.9, 206.3, 115.4, and 33.1 MIPS (millions of instructions per second), respectively [5]. In comparison, a handset processor such as Intel's StrongARM processor SA-1110 can deliver around 235 MIPS at 206 MHz [5]. A common goal of designing hardware and software for wireless handheld devices is to reduce battery power use and processor time as much as possible.

During an SSL session, only one cipher suite can be used at any time. Although SSL can change the cipher suite with a full handshake, doing so is inefficient because a full handshake entails communicationally expensive message interaction and computationally expensive public key certificate verification. Besides, SSL does not support restriction on channel directions, such as a simplex channel. SSL provides only a duplex channel, in which the cipher suites for both directions are identical. When requests and responses need different types of data protection, for example, an application cannot flexibly employ different cipher suites. In fact, few applications can change their cipher suites during an SSL session. This limitation is partially due to the high cost of changing cipher suites. As a result, data protection is coarse-grained.

There are several types of redundant protection. First, not all information is confidential, but it is still encrypted with confidential information using the same cipher in an SSL session. For example, a Web page for online banking contains confidential information, including account numbers and balances; however, other parts of the Web page, including HTML tags, JavaScript/Java code, images, advertisements, are not confidential. For example, after examining the HTML pages sent to Web browsers by one of the online-banking systems, we have determined that only around 4% of the data requires both integrity and confidentiality protection, with the rest needing just integrity or no protection at all [6]. For that latter data, expensive encryption operations are unnecessary, and HMAC (keyed-hash message authentication code) based on MD5 or SHA-1 can be adequate for providing data integrity. Our experiments with Java secure socket extension (JSSE) show that CPU savings could be up to 37% in those cases when 96% of data is nonconfidential and can be sent over an integrity-only channel [6]. This value could translate to a battery-life saving, but the relationship is different for each platform and user style.

Second, some information is already secured at the application layer. For example, some software, e-mail messages, and documents are already digitally signed or encrypted with digital certificates, PGP, or XML security. Extra protection by SSL is likely redundant in those cases. Third, many applications require authentication but do not need data protection after the login stage. In fact, different users and service providers have different security requirements. In summary, there is a need to support *selective protection*. Although choosing or switching between HTTP and HTTPS URL links can provide selective protection to some degree, it works only for Web applications at coarse granularity [7]. Applications require selective protection at finer granularity.

2.3. Weak negotiation capabilities

The third problem with SSL is the lack of sufficient information provided during the negotiation phase. To decide whether or not and how to use proxies, multiple cipher suites, and simplex channels, *C* and *S* must exchange sufficient information to make the right decisions that optimize the combination of different channels. Generally, *C* needs to inform *S* of its device capabilities and security policy. For example, *C* may define whether proxies are allowed to process data with sensitivity below a certain level, what cipher suites are strong enough to protect data with a certain level of sensitivity, and so on. Lack of negotiation support is SSL's third limitation. Moreover, the core of these limitations is that the negotiation and decision process of SSL does not take the security policies, device capabilities, and other important factors into account. These functional limitations constitute a mismatch between SSL and the diverse requirements of client-server applications. When handheld devices and mobile applications become more popular, this gap will likely become more apparent.

3. RELATED WORK

There are other methods for addressing the limitations described in Section 2, namely, changing cipher suites in SSL each time a different level of data protection is required, establishing several independent SSL connections, using SSL extension for a cleartext channel, employing ITLS, selectively protecting data using XML security technologies, and reducing associated costs by accelerating cryptographic operations. This section explains why none of these methods addresses the problems as adequately as MC-SSL.

There are several reasons why frequently changing cipher suites in SSL is unsuitable. First, an SSL client and SSL server do not have enough information—such as security policies and device capabilities—to decide if a new cipher suite is appropriate. Second, a full SSL handshake, including authentication and key exchange, is very inefficient for changing a cipher suite. Third, messages traveling in opposite directions often need different levels of protection, but it is very inefficient to change the cipher suite for each request or response by doing a full handshake. MC-SSL does not have these drawbacks.

A simple approach for improving the end-to-end security of the SSL proxy chain model is to have two simultaneous connections between **C** and **S**: a direct SSL connection and an SSL proxy chain. With both connections independent of each other, sensitive data would be transmitted only through the direct connection. This intuitive solution adopted by some applications (e.g., [8]) suffers from the need of the intermediate proxy **P** to impersonate **C** while authenticating to **S**. Generally, **P** cannot bind a connection with **S** to that between **C** and **S** using its own identity, even if **C** uses a

public key certificate for authentication. In contrast, proxies in MC-SSL are negotiated through the direct—also referred to in this paper as the "end-to-end"—channel before **C** starts to set up a proxy channel with **S**. Moreover, **P** can then use the session ID received from **C** for authenticating with **S**. In brief, a proxy in MC-SSL is authenticated as a proxy, not as a client.

Portmann and Seneviratne [7] propose a simple extension to SSL to obtain an extra cleartext channel. Their new record-type cleartext application data (CAD) adds a cleartext channel to an SSL connection. To some degree, this channel resembles a cleartext end-to-end channel in MC-SSL; however, their channel is permanent and independent, which makes it insecure with proxies even if no sensitive data goes through it, because undetected data can be injected into the channel by any proxy. Without MAC or a digital signature, a cleartext channel cannot prevent information tampering or injection, and nonsensitive data could be displayed side by side with sensitive data. For this reason, an obvious drawback of the CAD-based approach is that it is always present, even if it is considered both unnecessary and insecure for some applications. Moreover, a CAD-based approach can create only cleartext channels. In comparison, MC-SSL can provide a variety of channels, including proxy channels and end-to-end channels created with various cipher suites. Moreover, every channel is securely negotiated among client, server, and proxies.

Kwon et al. [9] propose integrated transport layer security (ITLS) to avoid information leakage at a WAP gateway. The goal of ITLS is to prohibit the WAP gateway from having access to the plaintext of messages exchanged between **C** and **S**. To achieve this, **C** encrypts a message twice for **S** and **P** using KC_S and KC_P, in that order. **P** decrypts the cipher text using KC_P and then sends it to **S**, which decrypts the data with KC_S. In reverse, **S** encrypts a message using KC_S and sends it to **P**. **P** encrypts it again using KC_P and then forwards it to **C**. **C** decrypts it twice using KC_P and KC_S to get the message. With ITLS, the gateway cannot perform content transformation and scanning, a limitation that MC-SSL does not have. In addition, ITLS requires a handheld device to perform encryption/decryption twice as often as SSL, further increasing the CPU time.

XML-based solutions to data protection such as XML security [10, 11] and Web services security (WS-security) [12–15] have the potential to solve the problems addressed by MC-SSL. XML-based solutions are different from MC-SSL in several aspects. First, they are not self-contained security protocols for client-server applications. That is, with just XML-based encryption/signing, mutual authentication and key exchange among client, server, and proxies cannot be performed individually; one has to rely on the security infrastructure. Second, XML-based solutions do not define mechanisms for negotiating different types of channels, while MC-SSL has such mechanisms. Third, XML-based solutions generally belong to the application layer. As such, they require both client and server to support XML and XML security, which is not optimal for those applications that exchange mostly binary data.

MC-SSL defines a protocol between transport and application layers, and works for a variety of applications, including Web services. Besides the above differences, MC-SSL has some advantages over XML-based solutions. First, MC-SSL is more efficient than XML-based solutions: the latter commonly require binary data to be transformed into text using base 64 encoding, which could significantly increase network traffic and CPU consumption for certain applications. Second, MC-SSL is an extension of SSL, and SSL is the de facto application security protocol with its implementations becoming commodities in most modern distributed environments. Therefore, we expect the cost of the transition from SSL to MC-SSL to be much smaller than to XML security.

SSL splitting [16] is a technique for guaranteeing the integrity of data served from proxies without requiring changes to Web clients. This technique reduces the bandwidth load on the server, while allowing an unmodified Web browser to verify that the data served from proxies is endorsed by the originating server. With SSL splitting, the Web server sends the SSL record authenticators, and the proxy merges them with a stream of message payloads retrieved from the proxy's cache. The merged data stream that the proxy sends to the client is indistinguishable from a normal SSL connection between the client and the server. SSL splitting is geared towards secure public file downloads, in which the concern is data integrity rather than confidentiality.

SSL splitting is similar to MC-SSL in that it is able to provide data integrity in the presence of a partially trusted proxy. In addition, MC-SSL can provide confidentiality by routing sensitive data via a direct channel, and less or nonsensitive data through a proxy channel. An MC-SSL proxy channel can have several proxies, whereas SSL splitting supports only one. Even though SSL splitting does not require modifications to the client as MC-SSL does, both approaches make changes to the protocol between the server and the proxy.

4. MC-SSL ARCHITECTURE

MC-SSL improves end-to-end security in the presence of application proxies by establishing proxy channels, and reduces redundant cryptographic protection by supporting channels with different cipher suites. MC-SSL can provide an application session with multiple-virtual channels. The negotiation of channels is based on security policies, device capabilities, and the security attributes of application data of both client and server.

In MC-SSL, a cipher suite consists of only two elements: a cipher for data encryption and decryption, and a hash algorithm for MAC, and hence can be denoted as follows:

$$\{\text{cipher and key size, hash algorithm for MAC}\}. \quad (1)$$

As shown in Figure 3, a connection in MC-SSL can have multiple cipher suites. We characterize a point-to-point connection as follows: {*endpoint 1, endpoint 2, key exchange algorithm*, {*cipher suite 1, cipher suite 2*, ...}}, where each cipher suite forms a channel. Every MC-SSL connection must first have a strong cipher suite (e.g., a 128-bit cipher plus

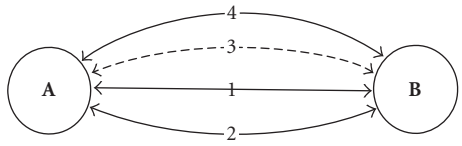


Figure 3: Multiple cipher suites inside a connection.

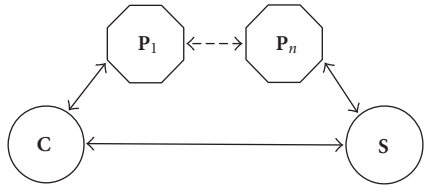


Figure 4: Proxy channel model of MC-SSL.

SHA-1) to form the primary channel, which provides the backbone for setting up and controlling other channels in the same connection. A primary channel is the first channel in an MC-SSL connection, and it can be set up with the unchanged SSL protocol. Other channels in an MC-SSL connection are referred to as secondary channels. They are new channels added to an SSL connection to support multiple cipher suites. The sample connection in Figure 3 can be characterized as {**A**, **B**, RSA, {CS1, CS2, CS3, CS4}}, where RSA is the key exchange algorithm, and CS1 through CS4 are cipher suites for channels 1 to 4, respectively. Among them, channel 1 is the primary channel.

The proxy channel model of MC-SSL is illustrated in Figure 4, in which the point-to-point connections collectively form an arc. **C**-**S** is termed an end-to-end channel, and **C**-**P**$_1$-$\cdots$-**P**$_n$-**S** is called a *proxy channel*. In this model, **C**-**P**$_1$-$\cdots$-**P**$_n$-**S** is a channel that relies on the **C**-**S** channel to perform channel negotiation and to transport application data. An *end-to-end channel* must exist before the proxy channel negotiation is started. Through an end-to-end channel, **C** and **S** exchange messages about what proxies they want and the other parameters of the proxy channel. After that, **C** and **S** interact with proxies to set up the proxy channel. The **C**-**S** channel is also used to control data transmission through the proxy channel. **C** or **S** can deliberately choose one of the two channels to transport data according to the data's security requirements. For example, sensitive information, such as passwords and credit card numbers, can be transported using the end-to-end channel. An MC-SSL session can have zero or more proxy channels. Each of them and the corresponding end-to-end channel reflect the proxy architecture shown in Figure 4.

Combining the proxy-channel architecture and multiple cipher suites leads to the multiple-channel architecture illustrated in Figure 5, with distinct SSL connections shown as cylinders. In MC-SSL, a channel is a protected communication "pipe," with a certain cipher suite and a number of application proxies. If there is no application proxy in the channel, then it is an end-to-end channel; if there is no cipher suite for the channel (the cipher suite is null), then it is a *plaintext*

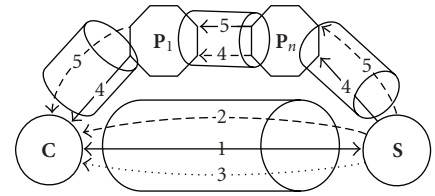


Figure 5: Multiple-channel architecture of MC-SSL.

channel. Additionally, a channel can be *duplex*, *simplex*, or *inactive*. The restriction on channel direction applies only to application data messages, not to channel control messages. An MC-SSL channel can be characterized as follows:

$$\text{channel} \equiv \{\text{ID}, E_1, E_2, \text{CS}, \{P_1, P_2, \ldots, P_n\}, D\}. \quad (2)$$

ID is a channel's identity number. E_1 and E_2 are either DNS names or the IP addresses of the corresponding endpoints. Cipher suite, CS, is defined by expression (1). A proxy (P_i) is identified by its DNS name or IP address. A channel can have zero or more proxies. Direction, D, indicates whether a channel is a duplex, an inactive, or a simplex one pointing to one of the two endpoints. An inactive channel cannot be used to transmit application data, but it can be used for transmitting channel control messages if it is a primary channel. Channel control messages can only go through primary channels.

We illustrate the MC-SSL architecture with Figure 5. The sample MC-SSL session has five channels. Among them, channels 1 and 4 are primary channels, and the others are secondary channels. Furthermore, channel 1 is the primary end-to-end channel, and channel 4 is a primary proxy channel; channels 2 and 3 are secondary end-to-end channels, and channel 5 is a secondary proxy channel. Note that an MC-SSL session can have multiple-primary channels. The number of primary channels in an MC-SSL session is equal to the number of SSL connections with **S** as an endpoint. Channels 2, 3, and 4 are negotiated through channel 1, and channel 5 is negotiated through channel 4. Additionally, only channel 1 is a duplex channel for application data; others are simplex channels from **S** to **C**. In this application scenario, **C** uses channel 1 to send encrypted requests to **S**, and **S** may choose one of the five channels to send back responses.

4.1. Application case study

In order to show that MC-SSL is practically useful, this section discusses the application of MC-SSL in Web applications. Suppose that we would like to use a handheld device to do online banking. In particular, we log into a banking Website, pay a bill, and check recent statements. However, the Web site is not compatible with the browser of the handheld device. We choose a proxy server provided by a wireless telecommunication company to perform transforming. We are not willing to expose password and financial information to the proxy although it is relatively trustworthy. How

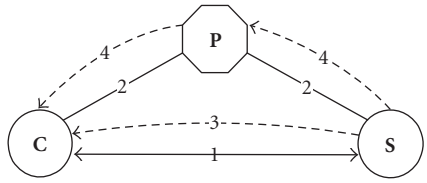


Figure 6: Channel planning for online banking.

can MC-SSL address this issue? First, let us consider what channels are required in this scenario. The primary end-to-end channel (channel 1 in Figure 6) is always necessary in an MC-SSL session. Moreover, channel 1 can be used to protect the ID/password pair and other sensitive data, including payment information, account number, and bank statements. Channel 3 is a MAC channel without encryption. The hash algorithm could be MD5 or SHA-1. The purpose of channel 3 is to transport content that needs end-to-end authenticity and integrity protection. To make use of the proxy service, the handheld device must negotiate a single-hop proxy channel (channel 4 in Figure 6) with the Web server. This channel is a simplex channel that only allows data traffic from the Web server to the handheld device. All HTTP requests generated by the handheld device are sent through channel 1, since it is hard for a Web browser, which does not know about specific application logic, to judge the sensitivity of data. Channel 4 is also channel protected only with MAC. Channel 2 is a primary proxy channel, which is used by MC-SSL to set up and manage channel 4, but it is not employed for transporting application data. Channels 3 and 4 can significantly reduce redundant encryption if they are used in the right way. For example, in a typical Web page for paying a bill, only the account number and payees' information is confidential. Other page content does not have to be encrypted by the Web server. On the other hand, if someone is not concerned about battery life and prefers extra data security, the Web server can simply use channel 2 without negotiating channel 4. Moreover, one can always choose not to use an application proxy, whether the handheld device can access a server or not.

A Web page contains roughly three types of content: the first type is the data that a Web page is created to carry, such as text, URL links, images, and sound; the second type is the data format, including HTML tags, fonts, size, colours; the third type is executable code such as JavaScript and Java. The first type can be sensitive or nonsensitive. The second type is relatively nonsensitive. The third type generally (with some exceptions) requires authenticity and integrity, but does not require confidentiality. Since all HTTP requests go through channel 1, the problem is how to send a Web page to **C**. It seems that **S** can simply use channel 1 to send all the sensitive data, channel 3 to send executable codes, and channel 4 to send formats of data to **P** for transforming, but how can **C** put data and codes back to a Web page after a Web page has been changed by **P**?

To solve this new problem, we can use HTML and XML tags and attributes to separate data from its formats and positions in an HTML page. Data can be kept in the same HTML page or be moved to a new URL. HTML attributes such as "datasrc," "datafld," and "src" can achieve this objective. The following is an example that separates data in a table from its tabular form.

```
<html>
  <body>
        <xml id="bs_data" src= "bs_data.xml"> </xml>
        <table border="1" datasrc="#bs_data">
           <tr>
                 <td> <span datafld="DATE"> </span> </td>
                 <td> <span datafld="DETAILS"> </span> </td>
                 <td> <span datafld="DC"> </span> </td>
                 <td> <span datafld="BALANCE"> </span> </td>
           </tr>
        </table>
  </body>
</html>
```

The following is bs_data.xml, which is the data source of the table.

```
<?xml version="1.0" encoding="ISO-8859-1"?>
  <ST_DATA>
    <TRANS>
       <DATE>2004-09-28</DATE>
       <DETAILS>payroll 23456</DETAILS>
       <DC>3000.00</DC>
       <BALANCE>51678.26</BALANCE>
    </TRANS>
    <TRANS>
       <DATE>2004-10-01</DATE>
       <DETAILS>cheque 00135</DETAILS>
       <DC>−600.00</DC>
       <BALANCE>51078.26</BALANCE>
    </TRANS>
</ST_DATA>
```

In this example, **S** can use channel 1 to transport the XML file, and channel 4 to process the HTML formats. However, "datasrc," "datafld," and "src" are not standard HTML attributes, even in the latest HTML 4.01 [17], although Microsoft Internet Explorer supports these attributes. Fortunately, XHTML (extensible hypertext markup language) [18], the successor of HTML, has defined embedding attributes: "src=URI" and "type=ContentTypes." These two attributes are used to embed content from other resources into the current element. The "src" attribute specifies the location of a source for the contents of the element, and the "type" attribute specifies the allowable content types of the relevant URI. The following are two examples:

(i) ,

(ii) <script src="popwin" type="application/x-javascript"/>.

By using embedded objects, files, or data, a Web page can be divided into various parts for different channels. However, if the proxy **P** is compromised, the attacker could modify the "src" or "datasrc" attribute, and thus a user could be

provided with tampered data. For the following reasons, this risk is minimal. First, Web browsers will not use URL links that point to a different Web site in a Web page protected by SSL or MC-SSL. Second, **P** cannot get confidential data because all data goes through the end-to-end channel. Third, **C** or **S** should choose a relatively trustworthy proxy to reduce this risk. In our example of online banking, a proxy server provided by a telecommunications company should be good enough, although a proxy server of the associated bank is better, if available. There are still some methods for minimizing the risk. For example, **S** can collect all URI/URL in a Web page and send a copy to **C** through channel 1 or 3. Alternatively, **S** can send the hash value of all URI/URL to **C**.

This data (de)multiplexing does require the additional cost of application development. However, the MC-SSL API designers could preserve the transparency between (Web) applications and SSL by providing an abstraction of several independent sockets for transmitting data between the client and server. Such modern software development techniques as aspect-oriented software development (AOSD) [19] have the potential for reducing the development effort by separating the concerns of data processing and transmission.

The benefit of selective protection is also demonstrated by using the channel planning illustrated in Figure 6. Channels 3 and 4 are used for nonconfidential data, and channel 1 for confidential data. Suppose that channel 1 uses 128-bit AES for encryption and MD5 for MAC, and channels 3 and 4 use MD5 for MAC protection. If 95 percent of a Web page is nonconfidential, 71% of the CPU time can be saved by channels 3 and 4. If the nonconfidential part is 80%, then MC-SSL can save 57% of the CPU time that is spent on cryptographic operations. In many cases, nonconfidential information could contribute to more than 95% of a Web page secured by SSL. Depending on what algorithms are negotiated for data encryption and MAC protection, MC-SSL channels can commonly save 45% to 90% of the CPU time spent on cryptographic operations.

5. PROTOCOL DESIGN

This section presents the MC-SSL protocol that implements the multiple-channel architecture. The MC-SSL protocol consists of seven protocols: initial handshake, primary proxy channel, secondary channel, channel cancellation, alert protocol, abbreviated handshake, and application data. Among them, initial handshake, primary proxy channel, and secondary channel are key protocols for establishing different types of MC-SSL channels. The following subsections describe the MC-SSL architecture and these three key protocols. Interested readers can refer to [20] for a detailed description of all MC-SSL protocols.

5.1. Protocol architecture

The left part of Figure 7 shows the Internet protocol stack with SSL, and the right part shows the protocol stack with MC-SSL. The MC-SSL-protocol is deliberately designed to consist of two layers: (1) the upper layer is a new layer—inserted between SSL and the application layers—that provides the application with new MC-SSL specific functionality, and (2) the lower layer is SSL. The upper layer of MC-SSL is responsible for the negotiation and control of channels, and is thus called the "MC" (multiple channel) layer.

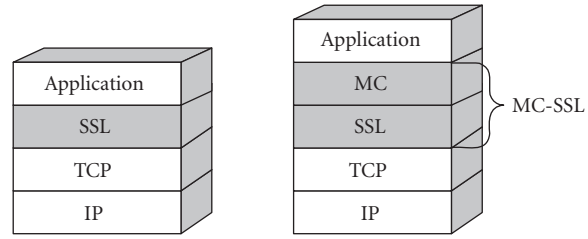


Figure 7: Two-layer architecture of MC-SSL.

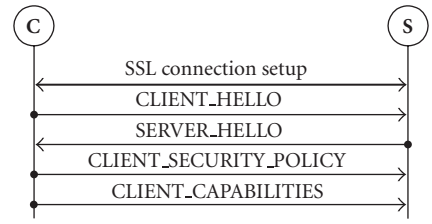


Figure 8: Initial handshake protocol.

The lower layer of MC-SSL, that is, SSL, remains untouched. SSL is therefore the basis of MC-SSL in terms of protocol design, software implementation, and security properties. Specifically, SSL is used for negotiating primary channels in MC-SSL. Although the MC-SSL protocol is implemented over SSL, the multiple-channel architecture of MC-SSL is not bound to SSL. For example, we believe that one can develop a new protocol from the MC architecture using XML security [10, 11] at the application layer.

5.2. Initial handshake protocol

The initial handshake protocol sets up the first channel, namely, the primary end-to-end channel. Figure 8 illustrates the handshake process. First, an SSL session is established between **C** and **S**. After that, **C** and **S** exchange messages to initiate an MC-SSL session. These messages, CLIENT_HELLO and SERVER_HELLO, contain the following information: protocol version, session ID, MAC key, and the hash algorithm for end-to-end MAC. The protocol version is the MC-SSL version number of **C** or **S**. The session ID is a cryptographically random string generated by the server to identify an MC-SSL session. The MAC key is used by the application data protocol to generate end-to-end MAC. Please refer to [20] for the message formats of the initial handshake protocol.

C then sends its security policy and device capabilities to **S** using CLIENT_SECURITY_POLICY and CLIENT_ CAPABILITIES messages. A security policy may define whether a proxy is allowed when **C** or **S** delivers information at a certain

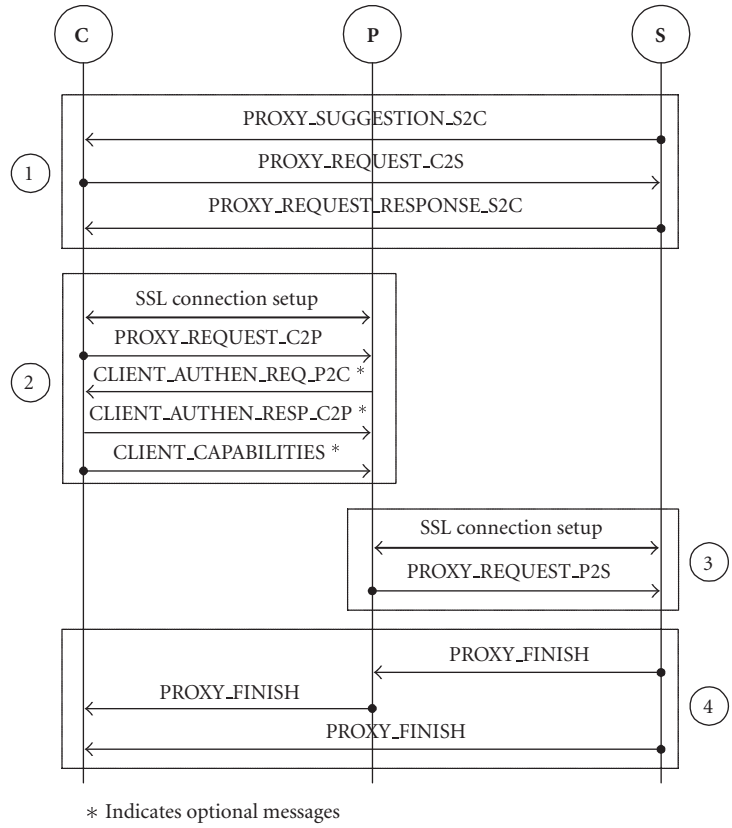


Figure 9: Primary proxy channel protocol.

level of sensitivity. The device capabilities include hardware and software information of a device such as CPU, power, memory, screen resolution, OS, browser capabilities. With such information about **C**, **S** is expected to make correct suggestions about what proxy channels and secondary channels are needed.

As can be seen from Figure 8, the MC-SSL initial handshake protocol carries communication cost of four messages, in addition to the SSL handshake, which costs 12 messages [1].

5.3. Proxy channel protocol

This section describes the proxy channel protocol, which can negotiate primary proxy channels—the backbone channels for negotiating and controlling secondary proxy channels. We first consider the protocol for a single-hop primary proxy channel, and then extend this protocol to the general case of a multihop primary proxy channel.

5.3.1. Single-hop proxy channel protocol

Figure 9 illustrates a complete protocol for establishing a single-hop proxy channel. It includes four stages: **C**-**S** handshake, **C**-**P** handshake, **P**-**S** handshake, and negotiation feedback. Apart from the SSL channel between **C** and **S**, which is set up by the initial handshake protocol, a single-hop proxy channel needs to set up two more SSL channels.

S or **C** can start the proxy-channel negotiation any time after the initial handshake of MC-SSL. In part 1 of Figure 9, **S** starts the negotiation by sending **C** a proxy-suggestion message (PROXY_SUGGESTION_S2C), which contains information about the proxy channel, such as the purpose of the proxy, the host name/address, and the certificate of the proxy, and channel direction. **C** then responds to **S** with a proxy request message (PROXY_REQUEST_C2S), which carries similar information about the proxy channel. In this message, **C** can use the proxy and channel parameters suggested by **S**, change some parameters, or even use a different proxy. **S** responds with the proxy request response message (PROXY_REQUEST_RESPONSE_S2C) to give its final decision. Please refer to [20] for the format of primary proxy channel protocol messages.

Both **C** and **S** can initiate a **C**-**S** handshake to negotiate a proxy channel. The **C**-**S** handshake can be interrupted if **C** or **S** decides that a proxy is insecure or unnecessary. In this handshake process, both **C** and **S** have a right to suggest, change, or veto channel parameters, including the proxy and the traffic direction. Further, proxies recommended by **C** and **S** for different purposes can be combined to form a multihop proxy channel. It is up to **C** and **S** to implement their

own (possibly application-specific) logic for determining the above parameters of the proxy channel.

The **C**-**P** handshake starts with the **C**-**P** SSL handshake. After that, **C** sends **P** a proxy-request message (PROXY_REQUEST_C2P), which contains the following information: the session ID, the proxy services needed, the channel direction, the authentication methods preferred by **C**, the handshake type, the IP address, and the port number of **S**. CLIENT_AUTHEN_REQ_P2C and CLIENT_AUTHEN_RESP_C2P are a pair of messages for **P** to authenticate **C**. The former informs **C** of the required authentication method, such as user ID/password, challenge/answer, or PKI certificate, and the latter returns the corresponding authentication data to **P**. If **P** does not require authentication or if it can authenticate *C* in a special way, these two messages may be omitted. Additionally, if **C** needs to provide its capabilities to **P** for **P** to perform its service, a CLIENT_CAPABILITIES message will follow. These optional messages are indicated in Figure 9 by an asterisk beside their names.

If **C** passes the authentication, **P** will set up an SSL connection with **S**, and then send a proxy request message (PROXY_REQUEST_P2S) to **S**. This message carries a session ID for **S** to bind the proxy channel with the end-to-end channel in the same session. The last three messages in Figure 9 return the result of this negotiation.

In the **P**-**S** handshake stage, there is no message for authentication. If **P** is a public or commercial proxy server, **P** can authenticate itself using its PKI certificate in the handshake process of SSL. However, **P** could be a home computer, which usually does not have a PKI certificate with a signature chain leading to a root CA (certificate authority). In this case, how can **P** authenticate itself to **S**? We believe that the session ID alone is sufficient for **P**'s credential. Because session ID is a cryptographically random bit string generated by **S**, and because it is exchanged as a secret using one of the primary channels among **S**, **C**, and **P**, it can serve as an acceptable token for authenticating **P** to **S**. Therefore, **P** does not have to possess a certificate acceptable by **S**. This is a useful feature because, for example, a handheld device user can designate a home computer as a proxy. For a handheld device to authenticate a home computer in the **C**-**P** handshake stage, a user can simply generate a certificate and its accompanying private key on the home computer, and import this "homemade" certificate into the handheld device before using the home computer as a proxy. The home computer can then authenticate to the server at the service provider site with the channel ID.

5.3.2. Multihop proxy channel protocol

A single-hop proxy channel is normally simpler and more secure than a multihop one. By using a proxy "cluster," in which one proxy works as the representative of other proxies to interact with **C** and **S**, one can substitute a multihop proxy channel with a single-hop one. However, multihop proxy channels are sometimes unavoidable for various reasons. This section describes the protocol for establishing a multihop proxy channel.

First, we consider the simplest way to extend the protocol described in the previous section: we can iteratively reuse the **P**-**S** handshake (i.e., stage 3 in Figure 9) on any two neighbouring proxies in Figure 4, for instance, from $\mathbf{P}_i$ to $\mathbf{P}_{i+1}$. Similar to a single-hop proxy channel, this forward process starts at **C** and ends at **S**. The proxy-request messages need small changes: they have to carry the parameters of all proxies, not just one. In the **C**-**S** handshake, **C** and **S** need to exchange information about DNS names, listening TCP ports, and even the certificates (or their URLs) of all the proxies. Likewise, the proxy-request message in the **C**-$\mathbf{P}_1$ handshake is extended to contain information about multiple proxies. The means of configuring client or server with the information about proxies is an important issue that has to be addressed by the system developers, no matter which approach is used to support multiproxy systems. This issue is, however, beyond the scope of this paper.

After the **C**-$\mathbf{P}_1$ handshake is performed, $\mathbf{P}_1$ connects to $\mathbf{P}_2$, and the **P**-**S** handshake occurs in the single-hop proxy-channel protocol. This forward process continues until the last proxy, $\mathbf{P}_n$, establishes a channel with **S**. The feedback process (i.e., stage 4 in Figure 9) can be easily extended for a multihop proxy channel without much change.

In addition to the handshake protocol described in the previous section, the total number of messages exchanged in sequential order is $4p + s(1 + p) + 7$, where s is the number of messages used for establishing an SSL connection and p is the number of proxies. If the cost of the MC-SSL initial handshake protocol also counted, the total cost becomes $4p + s(2 + p) + 11$ messages. For example, the overall communication cost of establishing a proxy channel with two proxies using SSL handshake (s is 12 messages) is 67 messages versus 36 messages needed for client and server to connect through the same two proxies using just three point-to-point SSL channels. Figure 10 shows the total communication cost (computed using the latter expression) of establishing a multihop connection for both MC-SSL and SSL. It suggests that the establishment of MC-SSL connections with few proxies costs twice as much as for SSL. However, the overhead of MC-SSL relative to SSL reduces as the number of proxies increases.

After this extended handshake process is completed, if we treat the structure in Figure 4 as a ring we can assure that every entity has authenticated its two neighbours. As a result, **C** can trust proxies from $\mathbf{P}_2$ to $\mathbf{P}_n$, and **S** can trust proxies from $\mathbf{P}_1$ to $\mathbf{P}_{n-1}$, assuming the trust relation created through mutual authentication is transitive. In the case of a single-hop proxy channel, there is no need for transitive trust because **C**, **P**, and **S** have directly authenticated one another. Although the simplest protocol extension requires transitive trust, we expect it to be good enough for most applications because proxy channels in MC-SSL are supposed to transport relatively nonsensitive data. Sensitive data should be transported using end-to-end channels.

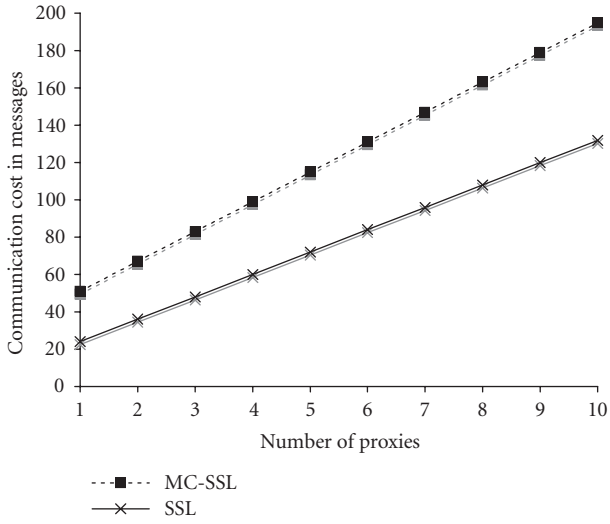


Figure 10: Communication cost of establishing simple multihop proxy MC-SSL and SSL connections with transitive trust assumption.

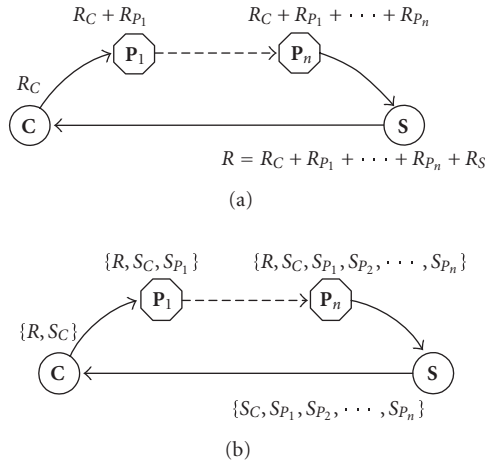


Figure 11: The enhanced authentication: (a) generating random string **R**, (b) signing **R**.

We can exclude the assumption of transitive trust by expanding the above negotiation process. If **C** and all proxies have their own certificates, the modified protocol would consist of the two stages illustrated in Figure 11. The intuition is simple: generate a random number and ask **C** and all proxies to sign the number using their private keys. The signatures are circulated and used to verify the public key of each participant by, potentially, each other.

Figure 11(a) shows the first stage, which generates a random string that is a concatenation of random numbers produced by all the entities in the loop. The resulting string can be denoted as $\mathbf{R} = \mathbf{R}_C + \mathbf{R}_{P1} + \mathbf{R}_{P2} + \cdots + \mathbf{R}_S$, where $\mathbf{R}_i$ is a 32-byte *cryptographically random* string generated by entity **X**, and "+" denotes the concatenation of two strings. This process starts and ends at **C**. The message from **C** to $\mathbf{P_1}$ contains only $\mathbf{R}_C$, while the last message, which **C** receives from **S**, is string **R**. In other words, each entity creates a random number $\mathbf{R}_i$. All numbers merge into a single string **R**, which is then signed by each entity using the corresponding private keys in the second stage. This method is actually an extension of SSL, where only two entities (i.e., **C** and **S**) are involved in the ring.

Figure 11(b) shows the second stage. $\mathbf{S}_i$ denotes the signature generated by the **i**th entity. **C** sends $\mathbf{P_1}$ a message that contains the random string (**R**) generated in the first stage, the certificate of **C**, and the digital signature ($\mathbf{S}_C$) generated upon **R** with **C**'s private key. The signature can prove that **C** is the key owner. Each proxy adds a new signature using its private key; meanwhile, each proxy can verify **C**'s identity using **C**'s certificate. When the message arrives at **S**, it has collected the signatures of all proxies, and therefore **S** can verify all of them using their certificates. **S** can also forward them to **C** if **C** wants to verify them as well. Section 5.3.1 claims that the proxy in a single-hop proxy channel may not need a PKI certificate since the session ID is randomly generated by **S**. This is not true for a multihop proxy channel, however, because any two neighbouring proxies have to authenticate each other. A multihop proxy channel is more complex than a single-hop one, and thus needs more support, such as public keys, from the security infrastructure.

For the first stage, we add a new field in proxy-request messages (PROXY_REQUEST_* in Figure 9) and the **S**-**C** proxy finish message to carry the random string, a flag field to indicate if **S** or **C** require verification of proxies' certificates, and another flag field to indicate if any proxy requires verification of **C**'s certificate. If no verification is requested, the second stage will not start. For the second stage, we also introduced a new message called CP_VERIFICATION to carry forward all the necessary information, which ends with a verification finish message (CP_VERI_FINISH) from **C** to **S**. While the messages of the first stage piggyback on proxy-request messages, the second stage comes with an additional cost of $2p + 2$ messages and the same number of signature generation and verification operations.

The protocol described above concerns the authentication of proxies and the client. We may also need to consider the security issues of transporting and processing application data through multiple proxies. For example, an application might require that every chunk of data goes through every designated proxy. To achieve this kind of data authenticity, the client/server can ask proxies to "sign" a data chunk using their private key or MAC key. However, this requirement introduces heavy computational costs in the case of many proxies. Since a proxy channel is not supposed to transport highly sensitive data unless all the proxies in the channel are sufficiently trusted, we decided not to have additional data authenticity protection at every proxy.

5.4. Secondary channel protocol

The protocols we have described so far do not support multiple cipher suites (a.k.a. secondary channels) in a point-to-point connection. The only channel in a connection that we have introduced is a primary channel provided by SSL.

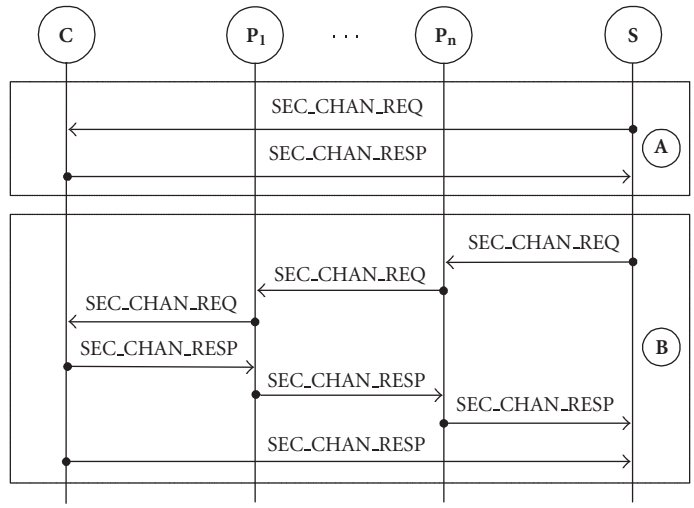


Figure 12: Negotiating secondary channels.

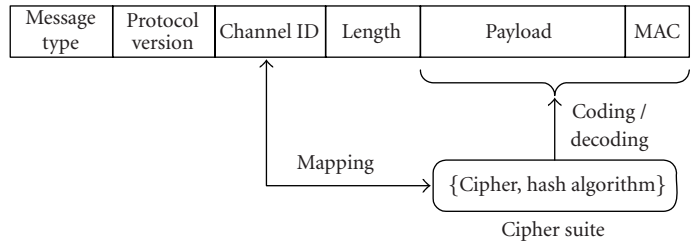


Figure 13: Adding channel ID in an SSL packet.

This section describes the protocol for establishing secondary channels. As defined in Section 4, every channel can have its own cipher suite and channel direction.

5.4.1. Negotiation of secondary channels

Figure 12 shows the process of negotiating of secondary channels. The negotiation of *secondary direct* channels is shown in part **A**, and the negotiation of secondary proxy channels is shown in part **B**. This protocol adds two messages to MC-SSL: the secondary-channel request message (SEC_CHAN_REQ) and the secondary-channel response message (SEC_CHAN_RESP). These messages are designed to carry requests and responses for multiple secondary channels to reduce message interactions if an application session needs multiple secondary channels. Additionally, they are designed to travel through primary channels. In MC-SSL, channel-control messages never travel through secondary channels, so that channel negotiation or management is as secure as through primary channels provided by SSL.

A SEC_CHAN_REQ message can specify the multiple secondary channels to be requested. The message carries the following information for each channel: the channel ID, a list of cipher suites preferred by the message sender, and the channel direction. It also carries the channel ID of the collaborative direct channel if the secondary channel is a proxy channel. The collaborative direct channel of a proxy channel is the channel that an APP_DATA_CONTROL_PROXY message travels through, and it can be the primary direct channel or a secondary direct channel. An SEC_CHAN_RESP message carries the responses for channel requests in an SEC_CHAN_REQ message. Please refer to [20] for the message formats of the secondary channel protocol. The overall communication cost of establishing a secondary proxy channel is $2p+5$, where p is the number of proxies in the channel.

For MC-SSL to efficiently support multiple cipher suites, a small extension is introduced to SSL. This extension is discussed in the next section. However, it is possible that the actual SSL implementation at **C** or **S** does not support the extension. In this case, the above negotiation process will either fail or not start, and secondary channels will not be available.

5.4.2. Extending SSL to support secondary channels

To multiplex several MC-SSL secondary channels in one SSL connection, we add a new field, *channel ID*, in every SSL packet header. When an SSL packet arrives, a receiver uses the cipher suite corresponding to the channel ID to decrypt and verify the payload encapsulated in the packet. Figure 13 illustrates an SSL packet and the relationship between channel ID, a cipher suite, and payload. The MC layer maintains the mapping between channel ID and a cipher suite.

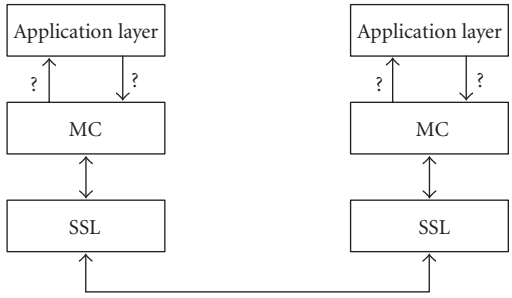


Figure 14: Implementation of channel directions.

Introducing a channel ID necessitates several changes to the SSL protocol. First, the calculation of MAC includes a channel ID. Second, an SSL implementation needs to choose the right cipher suite for each incoming packet according to the channel ID field. Third, some functions in the SSL library application programming interface (API) change: the write function has a channel ID as an input parameter, and the read function returns as an output parameter the ID of the channel from which the data comes.

Adding a channel ID field is a simple approach for supporting multiple cipher suites, but the downside is that the SSL header format has to be extended with an additional field. In [20], we describe an alternative for realizing secondary channels. The advantage of this approach is that it keeps the SSL protocol intact by "switching" the working cipher suites with a simple handshake protocol at the upper layer of MC-SSL. This technique changes a duplex channel into two simplex channels with two working cipher suites. Each endpoint maintains its own set of working cipher suites. Since two working cipher suites are maintained for two opposite directions of SSL, MC-SSL does not need to switch cipher suites in case one cipher suite is used for requests and a different one for responses. In brief, this method can reduce the frequency of switching cipher suites with the handshake protocol, but it cannot eliminate channel renegotiation if an application uses more than two simplex channels.

5.5. Restriction on channel directions

MC-SSL can restrict a channel's data-flow direction. The protocol defines four channel directions: *duplex*, *client to server*, *server to client*, and *none*. *Duplex* indicates a two-way channel. The next two directions indicate a simplex channel that allows application data to flow only from **C** to **S** or from **S** to **C**. Direction *none* is used for deactivating a channel. MC-SSL inhibits any application data flow over an inactive channel. Note that a primary channel can be used for channel-control messages in both directions even if it is marked as *client to server*, *server to client*, or *none*. This is because restriction on channel directions applies only to application data messages.

As shown in Figure 14, the restriction on channel directions is enforced at the interface between the application and the MC layers. If a channel is not duplex, it will reject receiving data from and/or delivering data to the application layer according to the specified channel direction. The underlying SSL layer is not aware of the channel directions imposed by the MC layer. In fact, there could be another duplex channel inside the same SSL connection that allows both receiving and delivering application data.

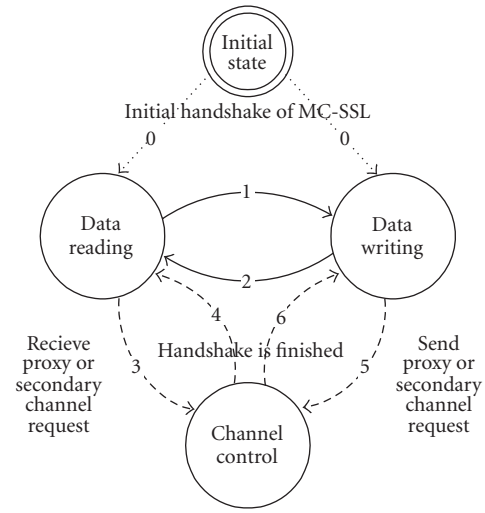


Figure 15: Basic state diagram of an MC-SSL session at a client or server.

6. PROTOTYPE IMPLEMENTATION

To assess the feasibility of the MC-SSL architecture and protocol, we have developed its prototype on Linux using OpenSSL [21]. Based on the protocol design, the prototype implementation has specified the message formats of MC-SSL protocol as listed in [20, Appendix B]. The message formats are defined using the language of TLS 1.0 specification [5].

After the initial MC-SSL handshake, the client and server applications establish the primary end-to-end channel through which they can start transporting application data or negotiating other channels. Figure 15 shows the basic state diagram of an MC-SSL session at **C** or **S**. There are four states in the diagram. The exit state is omitted since an MC-SSL session can exit from any state.

Starting from the initial state, an application could transfer to the data-reading or data-writing state, depending on the actual application protocol. For instance, an HTTP client enters a data-writing state, and an HTTP (Web) server enters a data-reading state. Applications at **C** or **S** can transfer between data-reading and data-writing states according to their predefined application protocol.

C and **S** can issue a request message to set up or cancel a channel at any time. As shown in Figure 15, MC-SSL automatically transfers from a data-reading state to a channel-control state after receiving a channel request. In contrast, it transfers from a data-writing state to a channel-control state when the application using MC-SSL calls an MC-SSL API function to send a channel request. In the channel-control state, MC-SSL is not supposed to receive or send any

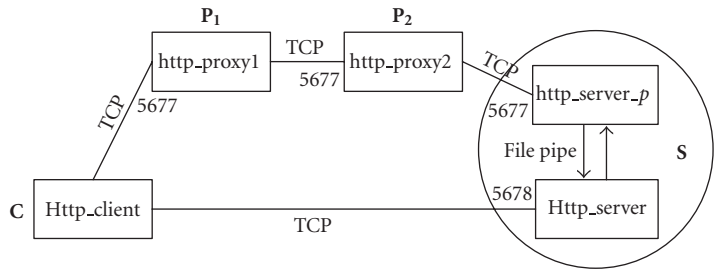


Figure 16: Prototype system diagram.

application data. When a channel-control process is finished, MC-SSL immediately returns to the state it was in before entering the channel-control state. As shown in Figure 15, if MC-SSL enters the channel-control state via edge 3, it goes back to the data-reading state via edge 4; similarly, it goes back to a data-writing state if it enters the channel-control state via edge 5.

6.1. Prototype configuration

Figure 16 shows the system diagram of the prototype. Server **S** is composed of two processes, http_server and http_server_p, both residing on the same host. The http_server_p is responsible for listening to and setting up a connection between http_proxy2 and http_server; therefore, it works like a local proxy at **S**. The http_server and http_server_p processes communicate using a pair of file pipes. The prototype assigns TCP port 5677 for proxy channels and TCP port 5678 for end-to-end channels. All server and proxy server processes in the prototype are implemented as multithreaded servers to provide HTTP over MC-SSL services to several concurrent clients.

The prototype demonstrates that the proxy and secondary channels of MC-SSL can be implemented over SSL and its extension. The prototype implementation of MC-SSL can be further extended or simplified according to a specific application scenario. For instance, the **C**-$\mathbf{P_1}$ connection could run over the WTLS/WDP protocol stack if both **C** and $\mathbf{P_1}$ support the WAP protocol stack. Other details about the proof-of-concept prototype can be found in [20].

7. CONCLUSIONS

This paper proposes multiple-channel SSL, a new architecture and protocol that is an extension of SSL. MC-SSL has three main features: first, it improves end-to-end security in the presence of partially trusted application proxies; second, MC-SSL supports secondary channels and channel direction restrictions so that appropriate data protection can be selectively applied to different data or content; third, MC-SSL supports channel negotiation according to security policies, device capabilities, and the security attributes of content. The MC-SSL architecture is more flexible than SSL, and hence it can better satisfy diverse requirements in different application scenarios, especially for emerging mobile applications.

MC-SSL comes with its costs and gains. The higher performance overhead is mainly due to the additional messages exchanged by the client, server, and proxies on top of the established SSL channels. Once MC-SSL channels are created, the only other performance cost is in the data (de)multiplexing over multiple channels, which is very much specific to the particular application and the number of secondary channels. Establishing a primary proxy channel costs $4p + s(2 + p) + 11$ messages, where p is the number of proxies and s is the communication cost (in number of messages) of establishing each underlying SSL connection. Furthermore, creating a secondary proxy channel costs another $2p + 2$ messages. A server experiences a total increase of 10 messages (in addition to the SSL connections) that it has to either generate or process when a client connects to it via proxies. On the other hand, selective protection, as we discussed in Section 4.1, can save CPU resources, a valuable asset for constrained mobile devices and overloaded servers. Depending on what algorithms are negotiated for data encryption and MAC protection, MC-SSL channels can commonly save 45% to 90% of the CPU time spent on cryptographic operations. We expect that the benefits due to MC-SSL and the amortization of the costs over long-lasting connections will outweigh the costs of establishing channels and (de)multiplexing data.

The MC-SSL protocol presented in this paper is only one possible implementation of MC-SSL architecture. The principles and the architecture can be applied to improve WTLS protocol or develop a counterpart protocol of MC-SSL for UDP applications. One can develop a similar security protocol on top of UDP so that applications such as VoIP can make use of proxy channels and multiple cipher suites. If two wireless terminals communicate with VoIP over RTP but do not support the same voice coding or compression scheme, they can use MC-SSL to set up a proxy for translating the voice encoding. In addition, they can use different cipher suites for user authentication and voice traffic.

ACKNOWLEDGMENTS

This work was supported by grants from Telus Mobility and the Advanced Systems Institute of British Columbia and by the Canadian Natural Sciences and Engineering Research Council under Grant CRD247855-01. The authors would like to thank Johnson Lee for conducting analysis of MC-SSL savings [6] and Craig Wilson for improving the readability of the paper.

REFERENCES

[1] T. Dierks and C. Allen, "The TLS Protocol Version 1.0," RFC 2246, January 1999.

[2] B. Schneier, *Applied Cryptography*, John Wiley & Sons, New York, NY, USA, 2nd edition, 1996.

[3] M. Y. Rhee, *Internet Security : Cryptographic Principles, Algorithms and Protocols*, John Wiley & Sons, New York, NY, USA, 2003.

[4] WAP Forum, WAP 2.0 Specifications, http://www.openmobilealliance.org/.

[5] S. Ravi, A. Raghunathan, and N. Potlapally, "Securing wireless data: system architecture challenges," in *Proceedings of the International Symposium on System Synthesis*, pp. 195–200, Kyoto, Japan, October 2002.

[6] J. Lee, V. C. M. Leung, and K. Beznosov, "Analysis of scalable security–MC-SSL savings," Tech. Rep. LERSSE-TR-2005-02, Laboratory for Education and Research in Secure Systems Engineering (LERSSE), University of British Columbia, Vancouver, BC, Canada, October 2005.

[7] M. Portmann and A. Seneviratne, "Selective security for TLS," in *Proceedings of the 9th IEEE International Conference on Networks (ICON '01)*, pp. 216–221, Bangkok, Thailand, October 2001.

[8] D. J. Kennedy, "An architecture for secure, client-driven deployment of application-specific proxies," M.S. thesis, University of Waterloo, Waterloo, Ontario, Canada, 2000.

[9] E. K. Kwon, Y. G. Cho, and K. J. Chae, "Integrated transport layer security: end-to-end security model between WTLS and TLS," in *Proceedings of 15th International Conference on Information Networking*, pp. 65–71, Oita, Japan, January-February 2001.

[10] W3C, XML Signature Recommendations, February 2002, http://www.w3.org/Signature/.

[11] W3C, XML Encryption Recommendations, December 2002, http://www.w3.org/Encryption/.

[12] OASIS Open, "Web Services Security: SOAP Message Security," http://www.oasis-open.org/committees/documents.php?wg_abbrev=wss, August 2003.

[13] OASIS Open, "Web Services Security X.509 Certificate Token Profile," working draft 11, October 2003, http://www.oasis-open.org/committees/documents.php?wg_abbrev=wss.

[14] OASIS Open, "Web Services Security Kerberos Certificate Token Profile," working draft 03, January 2003, http://www.oasis-open.org/committees/documents.php?wg_abbrev=wss.

[15] OASIS Open, "Web Services Security Username Token Profile," working draft 04, October 2003, http://www.oasis-open.org/committees/documents.php?wg_abbrev=wss.

[16] C. Lesniewski-Laas and M. Frans Kaashoek, "SSL splitting: securely serving data from untrusted caches," in *Proceedings of the 12th USENIX Security Symposium*, pp. 187–200, Washington, DC, USA, August 2003.

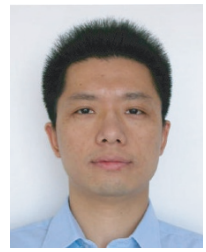
[17] W3C, HTML 4.01, December 1999, http://www.w3.org/TR/html4/.

[18] W3C, XHTML 2.0, July 2004, http://www.w3.org/TR/xhtml2/.

[19] G. Kiczales, J. Lamping, A. Mendhekar, et al., "Aspect-oriented programming," in *Proceedings of the 11th European Conference on Object-Oriented Programming*, pp. 220–242, Jyvaskyla, Finland, June 1997.

[20] Y. Song, "Multiple-channel security model and its implementation over SSL," M.S. thesis, University of British Columbia, Vancouver, BC, Canada, 2004, http://lersse-dl.ece.ubc.ca/search.py?recid=94.

[21] OpenSSL Project, 2004, http://www.openssl.org/.



Yong Song is a Database Engineer at Datawave Services Inc., Richmond, BC, Canada. He completed his Master's degree at the UBC in 2004 with the thesis on "Multiple-Channel Security Model and Its Implementation over SSL." Prior to UBC, Yong was a Software Engineer at Guangdong Telecommunication Academy of Science and Technology, China. He also received a Master's degree from South China University of Technology, and a Bachelor's degree from Huazhong University of Science and Technology, China.

Konstantin Beznosov is an Assistant Professor at the Department of Electrical and Computer Engineering, the University of British Columbia, where he founded and directs the Laboratory for Education and Research in Secure Systems Engineering (lersse.ece.ubc.ca). His primary research interests are distributed systems security, security and usability, secure software engineering, and access control. Prior to UBC, Dr. Beznosov was a Security Architect with Quadrasis, Hitachi Computer Products (America) Inc., where he designed and developed products for security integration of enterprise applications, as well as consulted large telecommunication and banking companies on the architecture of security solutions for distributed enterprise applications. Dr. Beznosov did his Ph.D. research on engineering access control for distributed enterprise applications at the Florida International University. He actively participated in standardization of security-related specifications (CORBA Security, RAD, SDMM) at the Object Management Group, and served as a co-chair of the OMG's Security SIG. Having published research papers on security engineering in distributed systems, he is also a coauthor of *Enterprise Security with EJB and CORBA* and *Mastering Web Services Security* both by John Wiley & Sons, Inc.

Victor C. M. Leung received the B.A.S. (honors) and Ph.D. degrees, both in electrical engineering, from the University of British Columbia (UBC) in 1977 and 1981, respectively. He was the recipient of many academic awards, including the APEBC Gold Medal as the head of the 1977 graduating class in the Faculty of Applied Science, UBC, and the NSERC Postgraduate Scholarship. From 1981 to 1987, Dr. Leung was a Senior Member of Technical Staff at MPR Teltech Ltd. In 1988, he was a Lecturer in Electronics at the Chinese University of Hong Kong. He returned to UBC as a faculty member in 1989, where he is a Professor and holder of the TELUS Mobility Research Chair in Advanced Telecommunications Engineering in the Department of Electrical and Computer Engineering. His research interests are in mobile systems and wireless networks. Dr. Leung is a Fellow of IEEE and a Voting Member of ACM. He is an editor of the IEEE Transactions on Wireless Communications, an associate editor of the IEEE Transactions on Vehicular Technology, and an editor of the International Journal of Sensor Networks.