iotops
Internet-Draft
Intended status: Informational
Expires: 26 June 2026

P. Liu, Ed.
R. Yang, Ed.
Pengcheng Laboratory
R. Chen, Ed.
China Mobile
R. Fu, Ed.
China Telecom
Y. Zhang, Ed.
Pengcheng Laboratory

23 December 2025

Modbus Serial Link Communication Security Protocol Reference Specification and implementation guide
draft-liu-iotops-modbus-seriallink-sec-spec-06

Abstract

The Modbus TCP protocol has adopted TLS-based security standards; however, Modbus serial communication over EIA/TIA-485 multi-point systems, commonly used in 2-wire or 4-wire configurations, lacks standardized security mechanisms. These systems support cable lengths exceeding 1000m at baud rates up to 9600 bit/s with AWG26 or thicker cables, while Category 5 cables can reach up to 600m. As an application layer protocol, despite its widespread application, the absence of encryption and authentication in Modbus protocol via serial links exposes plaintext data to risks such as MIM interception, modification under attacks such as side-channel analysis etc., particularly in long-distance or bridged network scenarios. Enhancing Modbus serial link security requires introducing proper encryption and authentication methods tailored to varied deployment environments onsidering the characteristics of serial links. A proposed security standard guide outlines lightweight encryption and authentication mechanisms to improve confidentiality and integrity while maintaining compatibility with existing Modbus devices, offering a practical upgrade path for secure industrial control systems.

Status of This Memo

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1. Introduction

The Modbus protocol with serial link communication as shown in Figure 1, is widely used in industrial communication, was not originally designed with security in mind. Its lack of encryption, authentication, and data integrity mechanisms makes it vulnerable to various cyberattacks, including replay, man-in-the-middle (MITM), and unauthorized access. Currently, for any EIA/TIA-485 multi-point system, whether it is a 2-wire or 4-wire configuration, the maximum length for cables with a maximum baud rate of 9600bit/s and AWG26 (or thicker) specifications can reach over 1000m. For RS485 Modbus, a sufficiently wide cable diameter should allow for a maximum length of over 1000m, and for RS485 Modbus using Category 5 cables, the maximum length can reach 600m. Currently, there is no relevant security communication standard for the existing Modbus serial link communication method. As an industrial communication protocol at the application level, with the evolution of precision attack technology, Modbus needs to provide targeted security technology standards for different deployment scenarios to continuously improve the Modbus industrial application security guarantee system and ecology. For example, in the presence of modern advanced hardware side channel attacks, especially in the case of long-distance relay serial or bridged networks, transmitting Modbus industrial control protocol data in plaintext over a fully serial link medium can easily lead to data leakage or malicious modification by intermediaries, posing serious data privacy or instruction security risks.

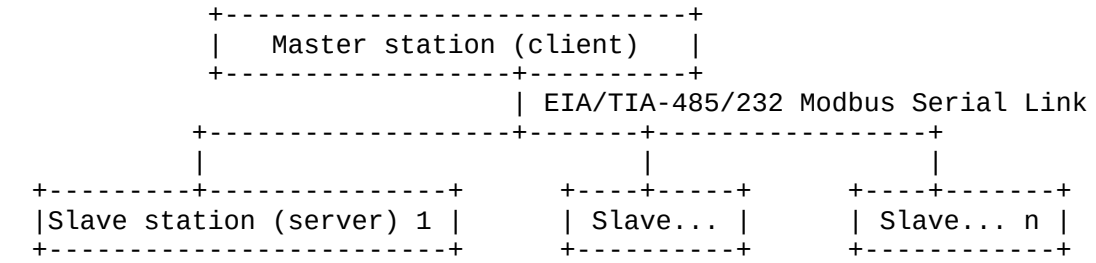


Figure 1: Modbus Serial Link Communication Network

For Modbus TCP, significant progress has been made to address these vulnerabilities. The Modbus Security Specification introduces Transport Layer Security (TLS) to encrypt and authenticate communications. TLS 1.2 or higher is mandated, ensuring protection against eavesdropping and MITM attacks. Additionally, X.509v3 certificates enable mutual authentication between clients and servers, while role-based access control (RBAC) allows granular security configurations. The Chinese standard GB/T 41868-2022 has

further expanded Modbus TCP security by adopting TLS encryption while maintaining compatibility with the original Application Data Unit (ADU) format. Modbus TCP Security uses IANA-registered port 802 for secure communication, providing a clear upgrade path for existing systems.

However, the security of serial link communication (e.g., RS485-based Modbus) remains an unresolved challenge. Serial Modbus transmits data in plaintext, leaving it susceptible to interception, modification, and hardware-based side-channel attacks. There are currently no formal standards addressing security for Modbus over RS485, which is still widely used due to its simplicity and long-distance capabilities. This lack of encryption and authentication mechanisms poses risks, particularly in scenarios involving relays or bridged networks. While Modbus TCP has seen notable advancements in security through TLS-based solutions, serial Modbus communication requires more attention. Introducing lightweight encryption and authentication mechanisms for serial links could provide a practical way to enhance security and protect legacy systems without significant infrastructure changes. Therefore, it is meaningful to improve and enhance the communication security of Modbus protocol under serial link mode, for reference by relevant institutions and organizations in various industries, in order to ensure the practical application security of various industrial control systems. With the introduction of the Modbus serial link security reference standard, the introduction of encryption and authentication mechanisms in the serial link communication channel of the Modbus protocol can significantly improve its security, providing a relatively simple and direct upgrade path reference for existing devices that use Modbus extensively.

2. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

3. Terms defined in this document

1. Trust anchor: An entity that is trusted by relying parties to validate the ownership, delegation, and authenticity of network resources. It serves as a root of trust for establishing and verifying resource allocation chains across multiple infrastructure services through cryptographic mechanisms and distributed consensus.

2. Modbus device: A device that implements Modbus on a serial link and follows its technical specifications.

3. Secure authenticated channel: A logical channel established using password methods between the master and slave stations that supports authentication and encryption of data.

4. Master client: The master client is a device on the serial communication link that sends instruction request and there is usually only one such device on a serial communication link.

5. Slave server: The slave client is a device on the serial communication link that sends instruction response. Generally, there can be multiple such devices on a single serial communication link.

6. Uimsbf: Unsigned integer most significant bit first

7. Bslbf: Bit serial leftmost bit first

4. Design Goals

The Modbus serial link communication security protocol specification aims to provide:

1. The Modbus serial bus security service definition, protocol specifications, system dependencies, and corresponding requirements for the Modbus serial link communication security protocol.

2. Reference application standards for institutions and organizations in the development or testing of Modbus serial communication security products

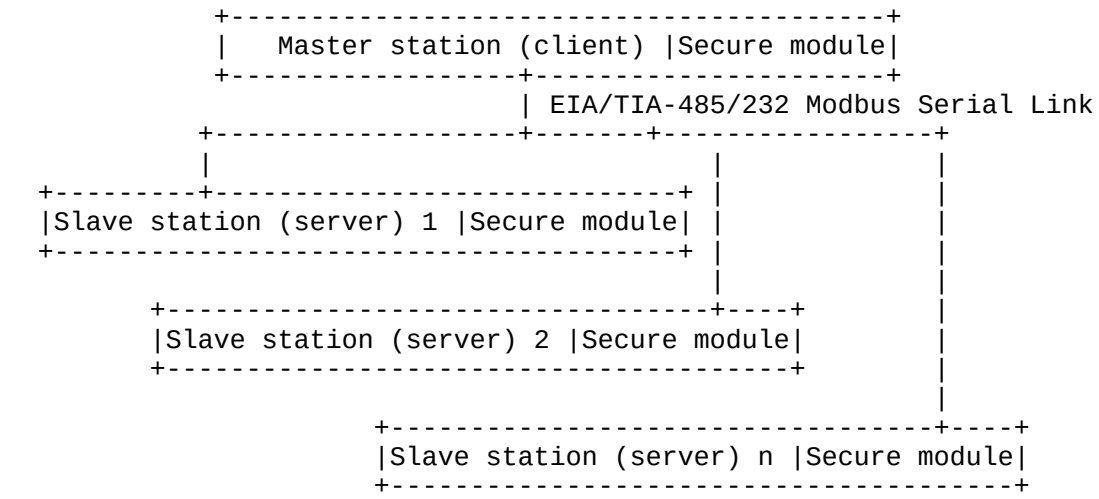
5. Modbus Serial Link Communication Security Protocol Specification

5.1. Modbus Serial Link Communication Security Service Definition

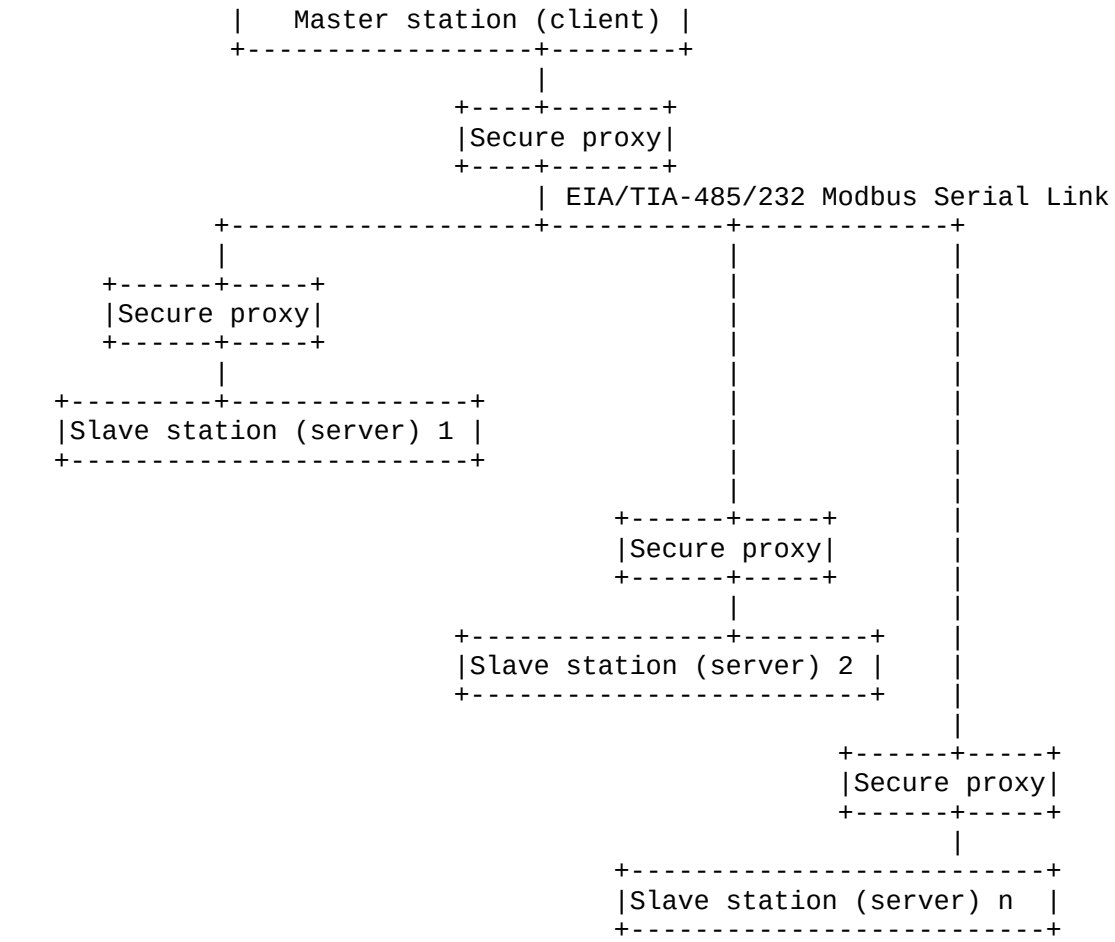
At present, according to the definition in the standard GB/T 19582.2-2008 and IEC 61158 CPF15 (FDIS)-2006, for Modbus serial links based on EIA/TIA-485-A and EIA/TIA-232-E, the standard requires any EIA/TIA-485 multi-point system, whether in a 2-wire configuration or a 4-wire configuration, to have a maximum length of 1000m for cables with a maximum baud rate of 9600bit/s and AWG26 (or thicker) specifications, and also explicitly requires that for RS485 Modbus, a sufficiently wide cable diameter should allow for a maximum length of 1000m, and for RS485 Modbus using Category 5 cables, the maximum length can reach 600m, currently there is no related security

standard for serial link communication scenarios. As an application level industrial communication protocol, with the evolution of more advanced attack technologies, it is very necessary and valuable to provide targeted security technology standards for different deployment scenarios to continuously improve the Modbus industrial application security guarantee system and ecosystem. For example, in the case of modern advanced hardware side channel attacks, especially in the presence of relay serial or bridged networks, transmitting Modbus industrial control protocol instructions and data in plaintext over a fully serial link medium can easily lead to data leakage or malicious modification by intermediaries, posing serious data or instruction security risks. Therefore, it is necessary to supplement, improve and enhance the intrinsic communication security of Modbus protocol under serial link mode, in order to adapt to various rich networking scenarios allowed in the related standards, for reference by relevant institutions and organizations in various industries, and to ensure the application security of various industrial control systems in actual operation.

Considering the various performance differences between master and slave devices in industrial networks, the implementation of the serial link secure communication function defined in this document can be achieved by (1) directly integrating relevant embedded security management modules on the master and slave devices, or (2) adding separate secure external modules or secure proxy modules to the master and slave devices, as shown in Figure 5. The specific implementation form is not within the scope of this document.



(1) Integrated embedded security module



(2) Independent external security module or security proxy module

Figure 2: Implementation form of reference function for Modbus security

The Modbus application layer protocol and its standard function codes used on serial links are described in detail in the national standards Modbus Security Specification, GB/T 19582.1-2008 and GB/T 19582.2-2008. The function code field of the Modbus data unit is encoded with one byte, and the valid function code range is decimal 1-255 (with 128-255 reserved for exception response). When sending a message from the client to the server device, the function code field notifies the server of which operation to perform, where the function code ’0’ is invalid. In the standard Modbus Security Specification, GB/T 19582.1-2008, the following function codes and sub-codes are not included in the content of this standard. These function codes and sub codes are specially reserved in the format of function codes/sub codes, or only function codes, and all sub-codes (0-255) are

reserved: 8/19, 8/21-65535, 9, 10, 13, 14, 41, 42, 90, 91, 125, 126, and 127. Please refer to Annex III of the standard GB/T 19582.1-2008. For the standard function codes defined in Modbus Security Specification, GB/T 19582.1-2008 and GB/T 19582.2-2008, this draft document does not make any modifications to the function definitions. In addition, this draft document does not occupy the valid business function code resources defined in the standard Modbus Security Specification, GB/T 19582.1-2008 to implement security service functions, while maintaining compatibility with the Modbus serial link protocol. This draft document defines the function code "0" for the serial link secure communication service, which occupies an 8-bit byte and is used to define the content related to the Modbus serial link secure communication protocol. Among them, the original Modbus serial link protocol function codes and data fields are included as relevant parameters in the security protocol data to ensure that the corresponding business function codes and data are confidential or complete during serial link communication.

In the secure mode of serial link communication, when using Modbus RTU transmission mode, the corresponding relationship between the original Modbus RTU frame and the Modbus secure RTU frame is shown in Figure 3, where the function code and data field of the original RTU frame are encrypted and included in protocol data field of the secure RTU frame:

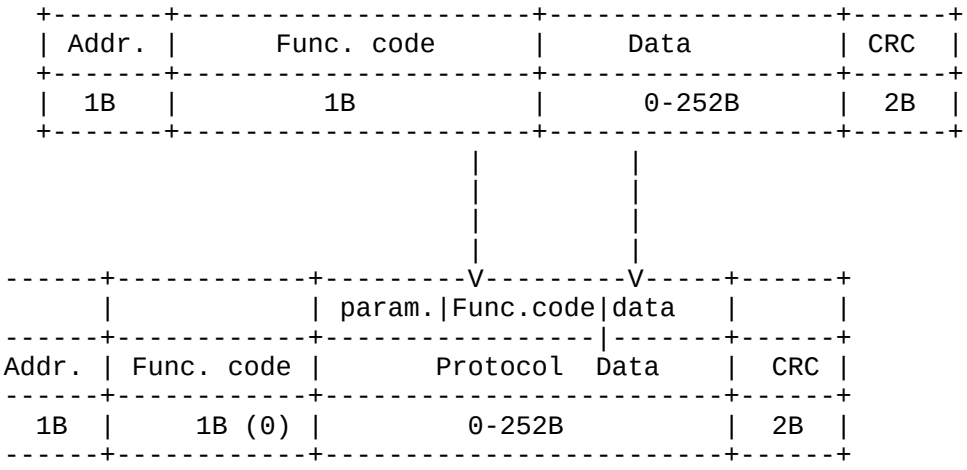


Figure 3: Modbus Secure RTU Message Frame

In the secure mode of serial link communication, when using Modbus ASCII transmission mode, the corresponding relationship between the original Modbus ASCII frame and the Modbus secure ASCII frame is shown in Figure 4, where the function code and data field of the original ASCII frame are encrypted and included in protocol data field of the secure ASCII frame:

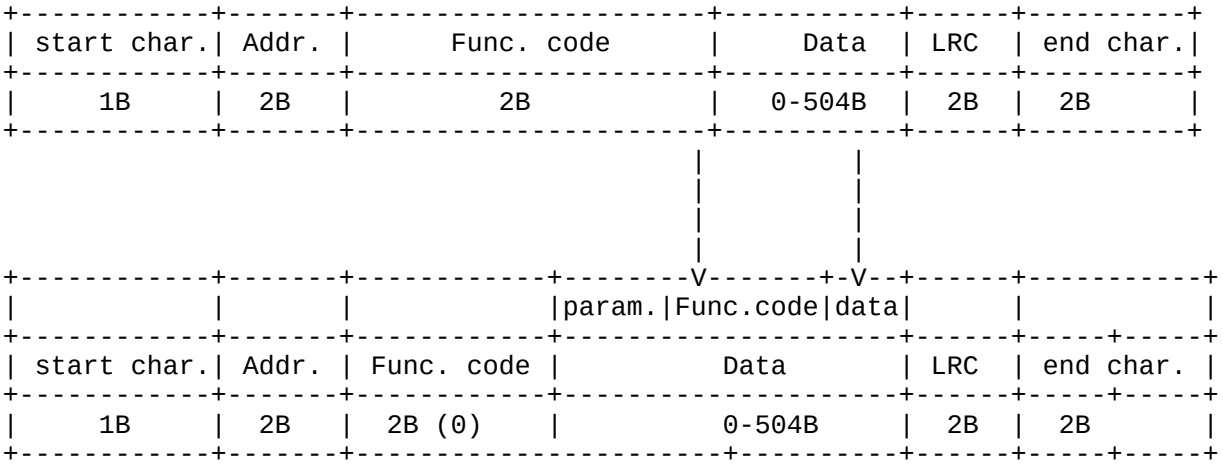


Figure 4: Modbus Secure ASCII Message Frame

5.2. Modbus Serial Link Security Protocol Reference Specification

5.2.1. System workflow

The Modbus serial link security protocol specification defined in this specification aims to protect the transmission of industrial control system protocol parameters between master/slave stations (clients/servers) through the serial bus interface using the Modbus protocol, ensuring that protocol parameters are not maliciously modified or intercepted by intermediaries. On a Modbus serial link, the master station on the serial bus acts as the client and the slave station acts as the server. The specific workflow varies depending on the security protocols used. This specification provides multiple security protocols for industry reference and implementation.

1) Modbus serial link security protocol based on ECC public key certificate is mainly implemented through the following six processes, which will be described separately in the following chapters.

1. Bidirectional public key authentication between client and server. When the client and server are bound for the first time, a mutual authentication protocol needs to be executed.

Successfully executing the protocol can make the client and server confident in each other’s reliability, and can also share a master key between both parties for secure processing of the protocol.

2. Re-authentication of client and server. On the basis of the first binding and sharing of the master key, the mutual authentication protocol is generally not executed when booting up again, but the re authentication protocol is executed.

3. SAC secure channel establishment. After successful authentication, the system enters the process of establishing the SAC secure channel. SAC secure channel is a secure channel established by the original Modbus protocol function code and data encryption and authentication key (referred to as content key).

4. Content key establishment. On the SAC secure channel, the client and server can establish content keys for encrypting the original Modbus protocol function codes and data.

5. Protocol function code and data encryption transmission. On the basis of establishing the content key, when sending a request, the client transmits the encrypted original Modbus protocol request function code and data to the server through Modbus secure RTU or ASCII message frames. The encrypted original Modbus protocol function code and data are decrypted and further processed on the server. When sending a response, the server transmits the encrypted original Modbus protocol response function code and data to the client through Modbus secure RTU or ASCII message frames. The encrypted original Modbus protocol function code and data are decrypted and further processed on the client.

6. For Modbus broadcast protocol interaction, based on the SAC secure channel, when establishing a content key, the client directly sends the corresponding individual broadcast content key to all slave servers on the bus. The content key for Modbus communication is the same for all slave servers. When sending a broadcast request, the client uses the broadcast content key to transmit the encrypted original Modbus protocol broadcast request function code and data to the server through Modbus secure RTU or ASCII message frames. The encrypted original Modbus protocol function code and data are decrypted and further processed on the server. When sending a response, the server uses the broadcast content key to transmit the encrypted original Modbus protocol response function code and data to the client through Modbus secure RTU or ASCII message frames. The encrypted original Modbus protocol function code and data are decrypted and further processed on the client.

2) The Modbus serial link security protocol based on passwords or pre-shared keys mainly includes the following four processes, which will be described separately in the following chapters.

1. Bidirectional authentication between client and server. When the client and server are bound for the first time, a mutual authentication protocol needs to be executed. Successfully executing the protocol can make the client and server confident in each other’s reliability, and can also share a master key between both parties for secure processing of the protocol.

2. Content encryption key establishment. The client and server establish two content encryption keys based on passwords or pre shared keys to encrypt and protect the original Modbus protocol function codes and data, one for broadcasting Modbus communication and the other for separate communication between the slave and master stations. The content key used for broadcasting Modbus communication is the same for all slave servers.

3. Protocol function code and data encryption transmission. On the basis of establishing the content key, when sending a request, the client transmits the encrypted original Modbus protocol request function code and data to the server through Modbus secure RTU or ASCII message frames. The encrypted original Modbus protocol function code and data are decrypted and further processed on the server. When sending a response, the server transmits the encrypted original Modbus protocol response function code and data to the client through Modbus secure RTU or ASCII message frames. The encrypted original Modbus protocol function code and data are decrypted and further processed on the client.

4. Regarding Modbus broadcast protocol interaction. When sending a broadcast request, the client uses the broadcast content key to transmit the encrypted original Modbus protocol broadcast request function code and data to the server through Modbus secure RTU or ASCII message frames. The encrypted original Modbus protocol function code and data are decrypted and further processed on the server. When sending a response, the server uses the broadcast content key to transmit the encrypted original Modbus protocol response function code and data to the client through Modbus secure RTU or ASCII message frames. The encrypted original Modbus protocol function code and data are decrypted and further processed on the client.

3) The Modbus serial link security protocol based on post quantum hybrid signature public key certificate mainly includes the following five processes, which will be described separately in the following chapters.

1. Bidirectional authentication between client and server. When the client and server are first bound, a certificate based bidirectional authentication protocol needs to be executed. Successfully executing this protocol can make the client and server confident in each other’s reliability, and can also share a master key between both parties, which can be used for protocol simplification and key derivation services.

2. Re-authentication of client and server. On the basis of the first binding and sharing of the master key, the mutual authentication protocol is generally not executed when booting up again, but the re authentication protocol is executed.

3. Content encryption key establishment. The client and server establish two content encryption keys based on post quantum encapsulation algorithm for encrypting and protecting the original Modbus protocol function codes and data, one for

broadcasting Modbus communication and the other for separate communication between the slave and master stations. The content key used for broadcasting Modbus communication is the same for all slave servers.

4. Protocol function code and data encryption transmission. On the basis of establishing the content key, when sending a request, the client transmits the encrypted original Modbus protocol request function code and data to the server through Modbus secure RTU or ASCII message frames. The encrypted original Modbus protocol function code and data are decrypted and further processed on the server. When sending a response, the server transmits the encrypted original Modbus protocol response function code and data to the client through Modbus secure RTU or ASCII message frames. The encrypted original Modbus protocol function code and data are decrypted and further processed on the client.

5. Regarding Modbus broadcast protocol interaction. When sending a broadcast request, the client uses the broadcast content key to transmit the encrypted original Modbus protocol broadcast request function code and data to the server through Modbus secure RTU or ASCII message frames. The encrypted original Modbus protocol function code and data are decrypted and further processed on the server. When sending a response, the server uses the broadcast content key to transmit the encrypted original Modbus protocol response function code and data to the client through Modbus secure RTU or ASCII message frames. The encrypted original Modbus protocol function code and data are decrypted and further processed on the client.

5.2.2. Modbus Serial Link Security Protocol Based on ECC Public Key Certificate

5.2.2.1. Key hierarchy structure

The key management in the Modbus serial link security protocol based on public key certificates is suitable for high-value and high security factories and devices. Its trust model can be found in Appendix C, and the key management scheme is divided into four levels: Credentials layer, Authentication layer, SAC secure channel layer, and Content key layer. The names, storage, and usage of the main parameters are summarized as below, where the requirement for random numbers generators can be found in Appendix B.

1. Root certificate: Certificate of system trust root, which is non-volatile storaged and local use.

2. Brand certificate: Brand certificate of device manufacturer, which is non-volatile storaged and used for exchange.

3. Device certificate: Public key certificates for the main and slave devices under the brand, which is non-volatile storaged and used for exchange.

4. EC_p: ECC Parameters, which is non-volatile storaged and local use.

5. EC_a: ECC Parameters, which is non-volatile storaged and local use.

6. EC_b: ECC Parameters, which is non-volatile storaged and local use.

7. EC_N: ECC Parameters, which is non-volatile storaged and local use.

8. EC_G: ECC Parameters, which is non-volatile storaged and local use.

9. MDP/HDP: Device Public Key, which is non-volatile storaged and exchange use.

10. MDQ/HDQ: Device private key, which is non-volatile storaged and local use.

11. DHX/DHY: The power of DH modular exponentiation operation, which is volatile storaged and local use.

12. DHPM/DHPH: The public key generated after DH modular exponentiation operation, which is volatile storaged and exchange use.

13. DHSK: DH key (master key), which is non-volatile storaged and local use.

14. AKM: Master authentication key, which is non-volatile storaged and local use.

15. AKH: Slave authentication key, which is non-volatile storaged and exchange use.

16. Ns_M/Ns_H: Random numbers used for SAC channel establishment, which is volatile storaged and exchange use.

17. SEK: SAC data encryption key, which is volatile storaged and local use.

18. SAK: SAC Data Authentication Key, which is volatile storaged and local use.

19. SIV: SAC initialization vector, which is non-volatile storaged and local use.

20. Kp: Precursor used to calculate CK key, which is volatile storaged and exchange use.

21. CK/BCK: Content encryption key for Modbus protocol function code and data, which is volatile storaged and local use.

22. CIV/BCKIV: Content encryption initialization vector, which is volatile storaged and local use.

The keys at the credentials layer mainly include ECC public cryptographic protocol parameters, private keys of the master client and slave server, and public key certificate chains. The public key certificate chain includes root certificates, brand certificates, and device certificates. The device certificate includes the device's ID number, ECC public key, and other attribute information of the certificate. The key data at this level is mainly used to execute authentication protocols. After device initialization, the certificate must not be changed or replaced. It is recommended to use mature OTP memory based on eFuse or Anti-Fuse technology, one-time programmable non-volatile memory, and data that cannot be reversibly modified after writing. The definition of protection methods for these data is not within the scope of this specification.

For the master client, the keys at the authentication layer are mainly DHSK and AKM; for the slave server, there are mainly two keys, namely DHSK and AKH. Among them, DHSK is a shared master key negotiated after a two-way authentication protocol, while AKM and AKH are exported by DHSK. These three keys are long-term keys that should be stored in the device's NVM and must be guaranteed not to be modified or intercepted by third parties. It is recommended to use a mature TEE environment, and the protection methods for these keys are not within the scope of this specification.

The SAC secure channel layer has two keys, SAK and SEK. The former is used for message authentication based on SAC, while the latter is used for message encryption based on SAC. The SAK and SEK keys are generated through the SAC initialization protocol executed by both parties and are temporary keys shared between the client and server. It should be stored in the NVM of the device and must ensure that it

cannot be modified or accessed by third parties. It is recommended to use a mature TEE environment, and the definition of protection methods for SAK and SEK keys is not within the scope of this specification.

The content key layer first generates the content key CK and an initial vector CIV based on the SAC secure channel, while generating the keys BCK and BCIV required for broadcast communication. Then, the content key CK and initial vector CIV are used to encrypt and decrypt Modbus communication data using AES. The generation of CK key and vector CIV key is led by the master client, and the slave server obtains the same CK key and vector CIV through the SAC secure channel. Both are generated temporarily, and under certain conditions, the system must update the content key to provide high-strength security. Please refer to the following chapters for detailed instructions.

The overall key generation and usage process is as follows:

After power on start-up, the master and slave devices first perform a power on self-test. If it is normal, the master client should check if it can be re authenticated after power on; If the master client and slave server devices have been successfully bound before, re authentication is not necessary. Under the premise of successful binding, the two stages of certificate verification, DH key exchange, and authentication key verification can be skipped and directly enter the SAC channel establishment process. Otherwise, SAC authentication key generation for identity authentication must be performed first; After the SAC channel is established, the master and slave devices enter the content key establishment process. After the SAC channel and content key are established, the master and slave devices use content key encryption to protect the corresponding business protocol parameters during business operation. If for some reason, such as connection establishment failure or device busy, the protocol runs out of time and SAC or content key cannot be updated in a timely manner, corresponding errors can be prompted to device users or administrators on the industrial site.

5.2.2.2. Certificate and identity authentication mechanism

Authentication based on public key certificates includes certificate verification and DH key exchange, as well as verification of intermediate authentication keys. Firstly, the authentication process of the first stage master client and slave server begins by exchanging their respective certificate chains and DH public keys. The master client must verify the certificate chain of the slave server and the checksum generated by the slave server, and similarly, the slave server must verify the certificate chain of the master

client and the checksum generated by the master client. During the verification process, the slave server will extract the CLIENT ID (64 bit data) from the master client's public key certificate, and similarly, the master client will also extract the SERVER ID (64 bit data) from the slave server's public key certificate.

Then, in the second stage, the data exchanged between the slave server and the master client using the authentication protocol in the first stage can obtain a long-term DH secret key and a long-term authentication key (This long-term authentication key can reduce the first stage of public key authentication operations when the master and slave devices are powered on for re authentication, as described in the "Authentication Context and Re-authentication" section later.). The authentication key is obtained by calculating the DH secret key and the IDs of both parties. Both parties should store the authentication key in NVM for future calculation of SAC secure channel encryption key and content key. Afterwards, the slave server will send a request to the master client to confirm the authentication key. Upon receiving the confirmation message, the slave server must compare the received key value with the stored key value. If the two match, it can prove that the master client is legitimate.

The steps of the device authentication protocol based on public key certificates are shown in Figure 5, and the message semantics and process are explained as follows:

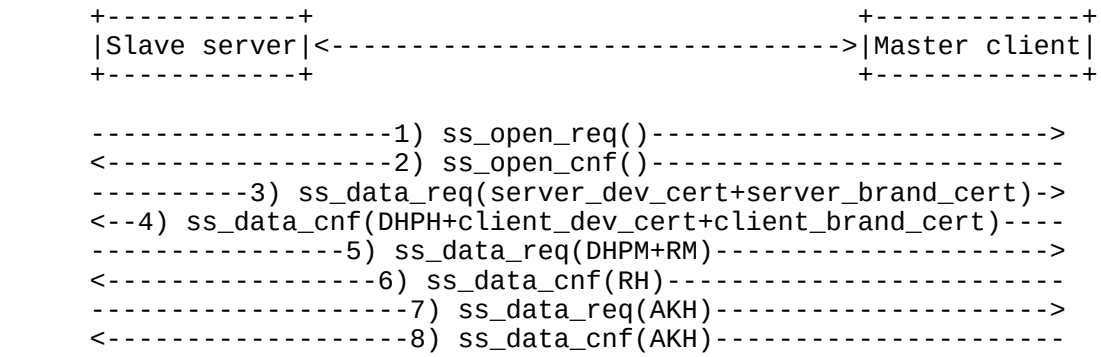


Figure 5: Authentication Message Exchange process

1. Send ss_open_req APDU from the slave server to the master client.

2. The master client responds with ss_open_cnf APDU.

3. Send ss_data_req APDU from the slave server to the master client. The message contains: 1) Device certificate (Server_dev_Cert) of slave server; 2) Brand certificate (Server_Brand_Cert) of slave server; 3) ID of the requested data type.

4. The master client responds with ss_data_cnf APDU. The message contains: 1) DH public key (DHPH) of master client; 2) Device certificate for master Client (Client_Dev_Cert); 3) Brand certificate (Client_Brand_Cert) of master client.

5. The slave server then sends the ss_data_req APDU. The message contains: 1) DH public key (DHPM) of slave server; 2) Verification value RM; 3) ID of the requested data type.

6. The master client responds with ss_data_cnf APDU. The message contains: 1) A verification value RH.

7. The master client responds with ss_data_cnf APDU. The message contains: 1) The data type ID of the requested AKH.

8. The master client responds with ss_data_cnf APDU. The message contains a AKH, Either it is valid or it is all zero, indicating illegality.

9. The slave server compares the received AKH with the locally calculated AKM.

1) The definition of ss_open_req APDU is as follows:

The slave server sends this APDU to inquire about the ID mask of the encryption system supported by the master client. The syntax is shown in Figure 6.

syntax	No. of bits	Mnemonic
ss_open_req() {		
ss_open_req_tag	24	uimsbf
length_field()=0		
}		

Figure 6: ss_open_req APDU syntax

1. ss_open_req_tag: 0x9F 90 01.

2. length_field: The length of the APDU payload, expressed in ASN. 1 BER format.

2) The definition of ss_open_cnf APDU is as follows:

The master client sends this APDU to the slave server, notifying them of the encryption system IDs supported by the slave server. The syntax is shown in Figure 7.

syntax	No. of bits	Mnemonic
ss_open_cnf() {		
ss_open_cnf_tag	24	uimsbf
length_field()=0		
ss_system_id_bitmask	8	bslbf
}		

Figure 7: ss_open_cnf APDU syntax

1. ss_open_cnf_tag: 0x9F 90 02.

2. ss_system_id_bitmask: Each of the 8 bits indicates the encryption system version supported by a master client. The slave server can choose the highest version supported by both ends. The lowest bit indicates version 1, there is no version 0. The encrypted version defined in this section is 1. ss_system_id_bitmask lowest position 1 (indicating support for version 1).

3) The definition of ss_data_req APDU is as follows:

The slave server sends an ss_data.req message to the master client to transmit protocol related data, while requesting a response from the master client. The ss_data_req APDU syntax is shown in Figure 8. ss_data_req APDU is used for data transmission that does not require authentication or encryption. Mainly used for authentication, authentication key verification, and SAC key calculation.

syntax	No. of bits	Mnemonic
ss_data_req() {		
ss_data_req_tag	24	uimsbf
length_field()=0		
ss_system_id_bitmask	8	bslbf
send_datatype_nbr	8	uimsbf
for (i=0;i<send_datatype_nbr; i++) {		
datatype_id	8	uimsbf
datatype_length	16	uimsbf
data_type	8*datatype_length	bslbf
}		
request_datatype_nbr	8	uimsbf
for (i=0; i<request_datatype_nbr; i++){		
datatype_id	8	uimsbf
}		
}		

Figure 8: ss_data_req APDU syntax

1. ss_data_req_tag: 0x9F 90 03.

2. ss_system_id_bitmask: Each of the 8 bits indicates the encryption system version supported by a master client. The slave server can choose the highest version supported by both ends. The lowest bit indicates version 1, there is no version 0. The encrypted version defined in this section is 1. ss_system_id_bitmask lowest position 1 (indicating support for version 1).

3. send_datatype_nbr: This message contains the number of data categories.

4. datatype_id: Data type ID, see Appendix A.

5. datatype_1ength: The byte length of datatype shaped data.

6. data_type: The specific data represented by datatype_id.

7. request_datatype_nbr: The number of data categories that the master client should include in its response.

8. datatype_id: The data number that should be included in the response of the master client, see Appendix A.

4) The definition of ss_data_cnf APDU is as follows:

The master client sends an ss_data_cnf message to transmit protocol related data to the slave server. The ss_data_cnf APDU syntax is shown in Figure 9. ss_data_cnf APDU is used for data that does not require authentication or encryption, mainly for authentication, authentication key verification, and SAC key calculation. For data that requires authentication or encryption, use ss_sac_data_cnf APDU.

syntax	No. of bits	Mnemonic
ss_data_cnf() {		
ss_data_cnf_tag	24	uimsbf
length_field()=0		
ss_system_id_bitmask	8	bslbf
send_datatype_nbr	8	uimsbf
for (i=0;i<send_datatype_nbr; i++) {		
datatype_id	8	uimsbf
datatype_length	16	uimsbf
data_type	8*datatype_length	bslbf
}		

Figure 9: ss_data_cnf APDU syntax

1. ss_data_cnf_tag: 0x9F 90 04.

2. ss_system_id_bitmask: Each of the 8 bits indicates the encryption system version supported by a master client. The slave server can choose the highest version supported by both ends. The lowest bit indicates version 1, there is no version 0. The encrypted version defined in this section is 1. ss_system_id_bitmask lowest position 1 (indicating support for version 1).

3. send_datatype_nbr: This message contains the number of data categories.

4. datatype_id: Data type ID, see Appendix A.

5. datatype_1ength: The byte length of datatype shaped data.

6. data_type: The specific data represented by datatype_id.

The protocol APDU format that includes specific data types in the authentication protocol is shown as follows:

When sending public key certificate chain from the slave server to the master client, ss_data_req APDU is sent with following Parameters in Figure 10.

content		
send _datatype_nbr=2		
i	datatype_id	datatype_len
0	11(Server_Dev_Cert)	1280 bits
1	4(Server_Brand_Cert)	1280 bits
request_datatype_nbr=3		
i	datatype_id	
0	8 (DHPH)	
1	10 (Client_Dev_Cert)	
2	3 (Client_Brand_Cert)	

Figure 10: ss_data_req APDU content

When the master client sends DHPH and two public key certificates, ss_data_cnf APDU is sent with following Parameters in Figure 11.

content		
send _datatype_nbr=3		
i	datatype_id	datatype_len
0	8(DHPH)	512 bits
1	10(Client_Dev_Cert)	1280 bits
2	3(Client_Brand_Cert)	1280 bits

Figure 11: ss_data_cnf APDU content

When sending DHPM and checksum RM from the slave server, ss_data_req APDU is sent with following Parameters in Figure 12.

content		
send _datatype_nbr=4		
i	datatype_id	datatype_len
0	9(DHPM)	512 bits
1	12(RM)	256 bits
2	11(Server_Dev_Cert)	1280 bits
3	4(Server_Brand_Cert)	1280 bits
request_datatype_nbr=1		
i	datatype_id	
0	20 (status_field)	

Figure 12: ss_data_req APDU content

When the master client sends the verification value RH, ss_data_cnf APDU is sent with following Parameters in Figure 13.

content		
send _datatype_nbr=1		
i	datatype_id	datatype_len
0	13(RH)	256 bits

Figure 13: ss_data_cnf APDU content

When requesting AKH from the slave server to the master client, ss_data_req APDU is sent with following Parameters in Figure 14.

content		
request_datatype_nbr=1		
i	datatype_id	
0	17(AKH)	

Figure 14: ss_data_req APDU content

When the master client sends AKH, ss_data_cnf APDU is sent with following Parameters in Figure 15.

content		
send _datatype_nbr=1		
i	datatype_id	datatype_len
0	17(AKH)	256 bits

Figure 15: ss_data_cnf APDU content

Note: During the certificate authentication phase, APDU messages will encapsulate the Modbus serial link data unit field with a success number of 0. For APDUs larger than 252 bytes (the maximum data field length of Modbus RTU frames), such as ss_data_req APDUs, which exchange certificates with approximately 422 bytes, they can be divided into two Modbus serial link message frames for transmission. Since the transmission operation is strictly serial and has a sequence, the upper layer application can concatenate two or more segmented APDUs based on the tag (ss_data_cnf_tag) and length_field () fields of the protocol.

The authentication process of the slave server is briefly described as follows:

1. Before starting the authentication process from the server, all sessions should have been opened;

2. Send its own certificate chain from the slave server;

3. The slave server waits for a response message from the master client;

4. The slave server must verify the validity of the certificate responded by the master client. If the certificate is invalid, proceed to step 19);

5. The slave server must verify the validity of the DHPH value. If it is invalid, proceed to step 19);

6. Generate a random DHY from the slave server;

7. Calculate the DH public key DHPM from the slave server;

8. The slave server must check if the DHPM value is valid. If it is invalid, proceed to step 19);

9. Generate verification value RM from the slave server;

10. Sending protocol data from the slave server;

11. The slave server waits for the master client to send back a response message;

12. The slave server must check whether the RH of the response from the master client is correct. If not correct, proceed to step 19);

13. Calculate AKM from the slave server;

14. Request AKH from the slave server to the master client;

15. The slave server should receive AKH within 5 seconds. Otherwise, proceed to step 19);

16. The slave server must check if the received response contains a valid AKH. If the received AKH is invalid, proceed to step 19);

17. The slave server must check whether the received AKH is consistent with AKM. If there is inconsistency, proceed to step 19);

18. The authentication of the slave server has been successfully completed;

19. Send error message (optional);

20. Authentication failed.

The authentication process of the master client is briefly described as follows:

1. Session is successfully opened;

2. The master client receives a certificate chain from the slave server;

3. The master client must check if the received certificate is valid;

4. The master client generates a random DHX;

5. The master client calculates the DH public key DHPH;

6. The master client must check whether the calculated DHPH is valid;

7. The master client sends DHPH and master client certificate chain to the slave server;

8. The master client is waiting for a response message from the slave server;

9. The master client must verify that the DHPM received from the slave server is valid;

10. The master client must verify whether the received slave server checksum is valid;

11. The master client calculates the verification value RH;

12. The master client sends RH to the slave server;

13. The master client calculates AKH;

14. Authentication successful;

15. Any error will result in authentication failure;

16. The master client receives a request from the slave server;

17. The master client responds with AKH value;

18. Authentication completed.

Note: The slave server can repeatedly send requests to AKH until the master client responds.

The calculations involved in the certificate based authentication process are shown in Figure 16, and described as below.

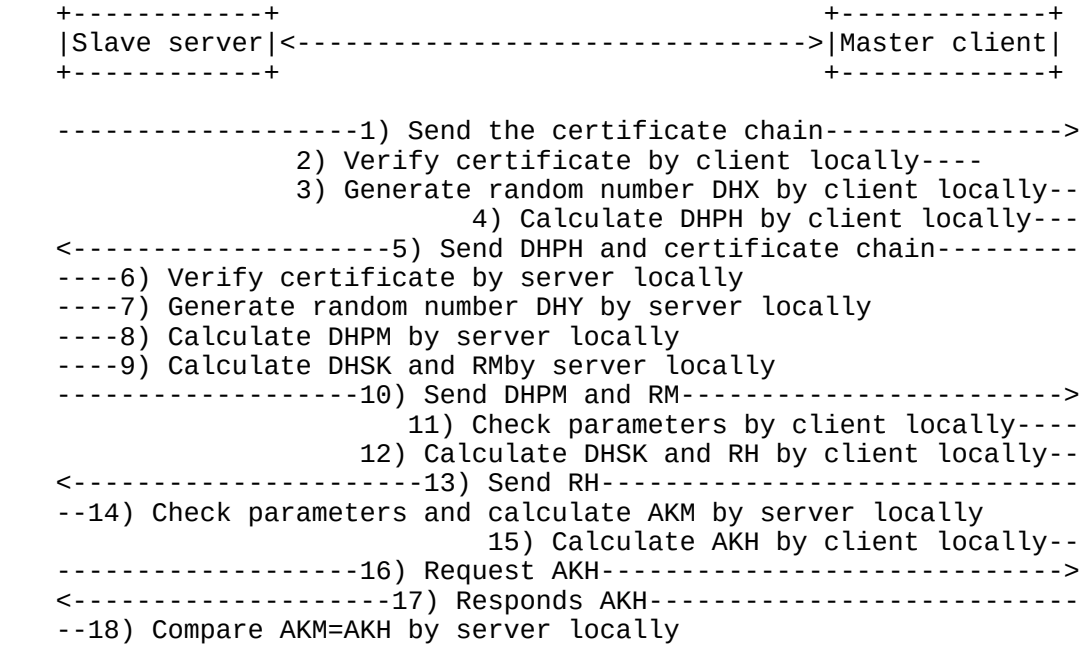


Figure 16: Calculation steps involved in the authentication process

1. The slave server sends its public key certificate chain to the master client

2. The master client verifies the validity of the two received certificates from the slave servers.

3. The master client uses an appropriate PRNG to generate a random DH exponent x (DHX).

4. The master client calculates its own DH public key (DHPH).

5. The master client sends the DHPH, master client device certificate, and master client device brand certificate to the slave server.

6. The slave server verifies the validity of the two certificates received from the master client.

7. The slave server generates a random DH exponent y (DHY) using an appropriate PRNG.

8. The slave server computes its own DH public key (DHPM) .

9. The slave server calculates the verification value RM as follows: a) Firstly, use the inverse element MDQ-1 of its private key to calculate xG = E_M(MDQ-1, DHPH); b) Calculate and store DHSK= E_M(y, xG); c) Calculate RM=SM3 (xG||DHPM||DHSK||SERVER ID); Note: E.M (*, *) represents scalar multiplication on an elliptic curve, where the first parameter is an element in a finite field and the second parameter is a point on the elliptic curve.

10. The slave server sends DHPM and RM to the master client.

11. The master client verifies the received parameters as follows: a) Firstly, use the inverse element HDQ-1 of the private key to calculate yG = E_M(HDQ-1, DHPM); b) Calculate and store DHSK = E_M(x, yG); c) Calculate RM ’= SM3(xG||DHPM||DHSK||SERVER_ID); d) Verify whether the received RM is consistent with the calculated RM ’. Note: E.M (*, *) represents scalar multiplication on an elliptic curve, where the first parameter is an element in a finite field and the second parameter is a point on the elliptic curve.

12. The master client uses the data calculated in steps 4) and 11) to calculate the verification value RH: RH = SM3(yG||DHPH||DHSK||CLIENT_ID).

13. The master client sends RH to the slave server.

14. The slave server verifies the received parameters using the data calculated in steps 7) and 9): a) Calculate RH ’= SM3(yG||DHPH||DHSK||CLIENT_ID); b) Verify whether the received RH is consistent with the calculated RH ’. The slave server calculates and stores the authentication key (AKM).

15. The master client calculates and stores the authentication key (AKH).

16. The slave server start to enter the second stage of the authentication process: request the current authentication key AKH from the master client through the response APDU.

17. The master client uses the corresponding APDU to send AKH to the slave server.

18. The slave server compares the received AKH with its own calculated AKM. If they are different, it will result in a system error.

The DH public keys (DHPH and DHPM) are temporary data that should be cleared and deleted after the authentication protocol is completed.

The DH public key is calculated as follows:

DHPH＝E_M(x, MDP), DHPM＝E_M(y, HDP)

Note that in the above equation:

The values x (DHX) and y (DHY) are generated by the built-in PRNG of the device. The values of x (DHX) and y (DHY) should be kept secret locally and cleared and deleted after the authentication protocol ends. In order to generate secure protocol parameters, after the master client calculates DHPH, the following checks must be performed:

DHPH is neither an infinite point nor a generator G, and the value of E-M (EC-N, DHPH) is an infinite point.

Similarly, after calculating DHPM from the station server, the following checks must be performed:

DHPM is neither an infinite point nor a generator G, and the value of E-M (EC-N, DHPM) is an infinite point.

The authentication keys (AKH and AKM) can be used in the calculation process of SAC keys and CK. The authentication key is generated when the master client and slave server are first bound and stored in NVM, which can be used for repeated authentication in the future. The calculation process is as follows:

AKM = AKH = SM3(SERVER_ID||CLIENT_ID||DHSK)

The relevant parameter columns are shown in Figure 17.

Parameter	No. of bits	description
DHSK	512	The DH secret key shared during the authentication process.
CLIENT_ID	64	Included in public key certificate of the master client device.
SERVER_ID	64	Included in public key certificate of the slaver serve device.

Figure 17: Parameters in Authentication Key Calculation

Authentication context and re-authentication: Authentication context is a secure data object stored in NVM, and its storage format is not strictly defined in this specification. However, in the implementation of actual products, it should be given sufficient security to ensure that it is not changed by attackers. The authentication context is used to store the results of public key authentication between both parties of the device, and is used to perform the re authentication process. The information that should be included in the authentication context of the slave server and master client is shown in Figure 18.

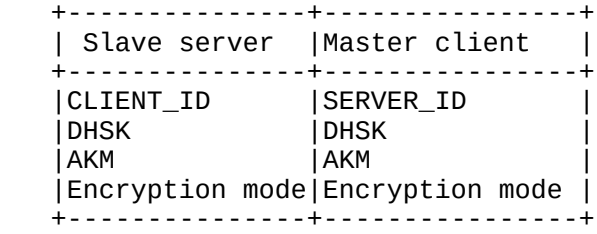


Figure 18: Information in Authentication Context

After the master client and slave server are first bound, the device should associate the DHSK and authentication key negotiated during the public key authentication process with an authentication context. The master client should support at least 247 authentication contexts, and the slave server should support at least 1 authentication context.

After establishing a session, the master client and slave server can first perform an authentication key verification step to check if there is an existing binding relationship between the two devices. If there is, there is no need to perform a public key authentication protocol. If the slave server has a valid authentication context, it should directly request the master client to send an AKH and then check if the received AKH matches the AKM in the local authentication context. If there is inconsistency, the slave server shall attempt up to 246 more times (as the master client may have 247 authentication contexts). When there are no other available authentication contexts for the master client, the master client should send a zero value as a response to the AKH request from the slave server, and the slave server should start executing the public key authentication protocol. If the master client has the authentication context of the slave, it should first send the AKH in the context of the slave. If the AKH is inconsistent with the AKM of the slave server, the slave server should attempt to request AKH again, and the master client should send other AKHs in other authentication contexts. So, re-powering on the slave server may not necessarily execute the public key authentication protocol to reduce authentication time. But when the slave server accesses an unbound master client, or when the master client accesses an unbound slave server, the identity authentication protocol related to the public key certificate is required to be executed.

5.2.2.3. Establishing secure authentication channel Mechanism

After authentication is completed, the protocol will establish a secure authentication channel (SAC), which is mainly used for content key establishment and transmission. Figure 19 is a schematic diagram of its function.

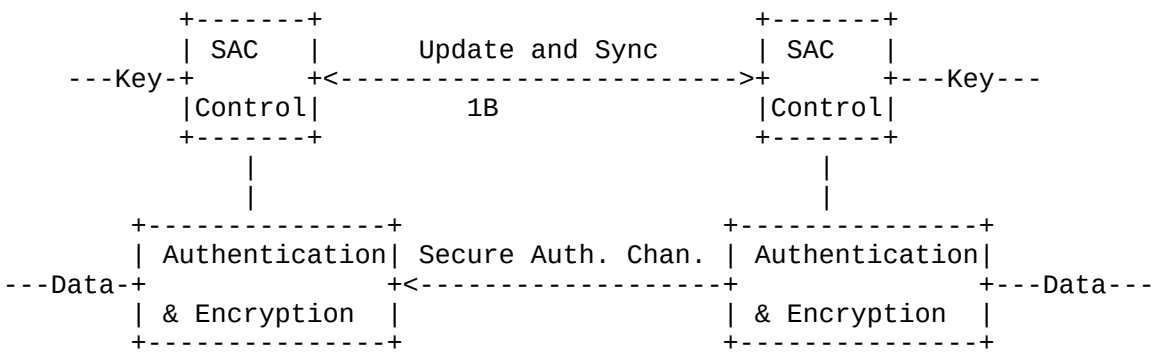


Figure 19: Schematic diagram of SAC function

Figure 20 shows the workflow of SAC channel establishment, which is described as follows.

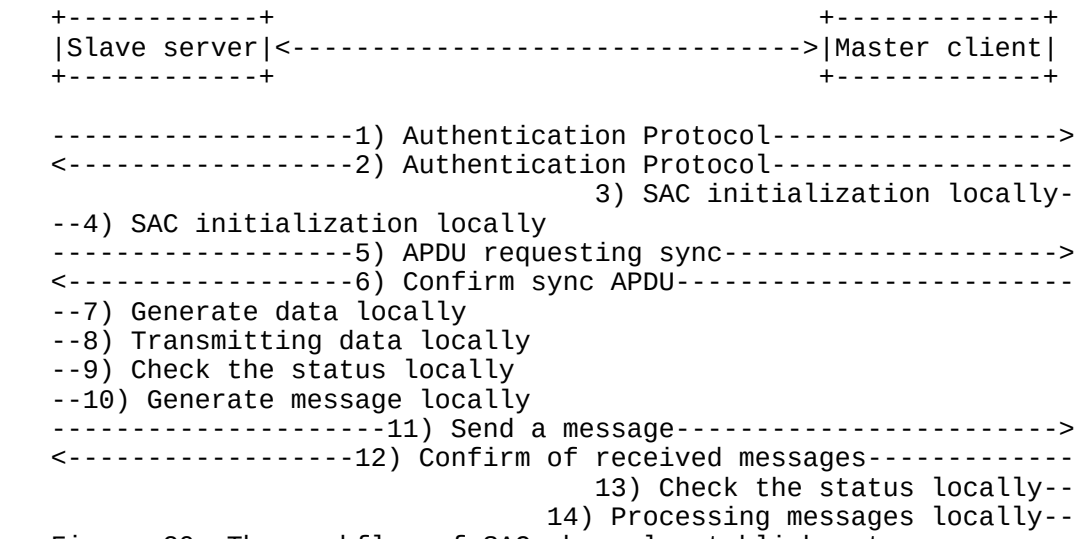


Figure 20: The workflow of SAC channel establishment

1. 1),2) Authentication protocol. The slave server and master client must have successfully executed the mutual authentication protocol.

2. 3),4) SAC initialization. Both the slave server and the master client need to first perform SAC initialization to generate key data and set the initial state of SAC.

3. 5),6) SAC synchronization request and confirmation. If the slave server has correctly initialized SAC, the slave server should send an APDU requesting synchronization to the master client. After the master client successfully responds, both parties can start using SAC.

4. 7)-11) Generate and send SAC messages. Generate SAC messages by adding message headers and authentication domains to the payload and encrypting them (optional).

5. 12)-14) Receive and verify SAC messages. Validate the received SAC message and proceed with further processing under the condition that the message is valid. Note: SAC can be used for bidirectional sending and receiving of messages;

Figure 21 shows the SAC initialization process, which is described as follows.

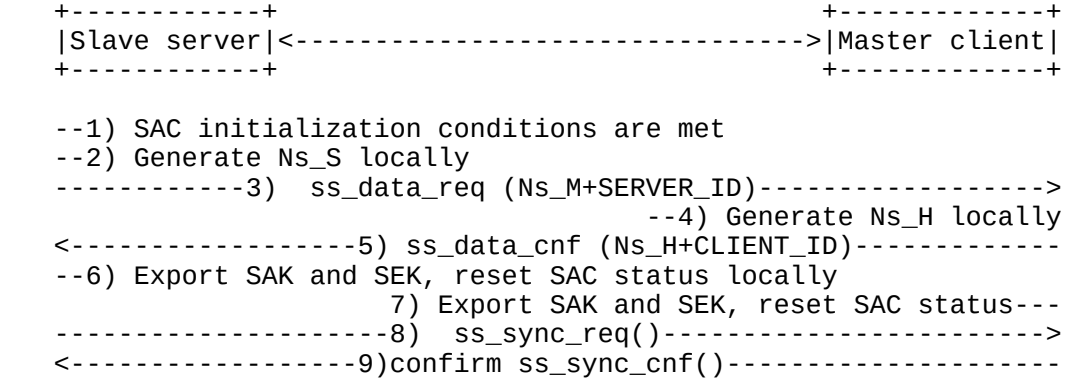


Figure 21: The workflow of SAC channel establishment

1. When the slave server detects that the conditions are met, it initiates the SAC initialization process.

2. The slave server generates a random number Ns_S, which is used as part of the data involved in SAC key calculation.

3. The slave server sends the ss_data_req APDU to the master client, including the following parameters: 1) Ns_M; 2) SERVER_ID.

4. The master client generates a random number Ns_H, which is used as part of the data for SAC key calculation.

5. After receiving the ss_data_req APDU from the slave server, the master client should respond to the slave server with the ss_data_cnf APDU, which includes the following parameters: 1) Ns_H; 2) CLIENT_ID.

6. The slave server checks whether the received CLIENT_ID matches the pre-stored one. If they match, start calculating SAK and SEK and set or reset SAC status. If they do not match, it will cause a system error. Note: The pre-stored SERVER_ID/CLIENT_ID is in the "authentication context".

7. The master client checks whether the received SERVER_ID matches the pre-stored one. If they match, start calculating SAK and SEK and set or reset SAC status. If they do not match, it will cause a system error. Note: The pre-stored SERVER_ID/CLIENT_ID is in the "authentication context".

8. The slave server sends ss_stync_req APDU to the master client to indicate that the master client SAK needs to be refreshed. When the slave server has completed initialization, it will send a synchronization request indicating that the slave server is ready to use SAC.

9. The master client sends ss_sync_cnf APDU to the slave server as a confirmation response, indicating that the master client is also ready to use SAC.Failure to respond to ss_sync_cnf messages will result in a system error.

The SAC initialization protocol is initiated by the slave server and passively responded by the master client. The re-initialization process is optional. This protocol is triggered by the following conditions:

1. Power on restart; After system start-up or restart and there is a valid AKM in NVM.

2. Certification; When there is no valid AKM in NVM, the system will enter the re authentication protocol, and after the authentication protocol is completed, trigger the SAC initialization protocol.

3. Message counter overflow.

4. System allows SAC to reinitialize.

APDU definition used during SAC initialization process:

The definitions of ss_open_req and ss_open_cnf APDU are the same as those in the authentication mechanism in the previous section.

1) ss_sync_req APDU

Used for SAC key calculation, the slave server sends the APDU after the key calculation is completed to indicate that it is ready to use the newly calculated key. The syntax of ss_sync_req APDU is shown in Figure 22.

syntax	No. of bits	Mnemonic
ss_sync_req() {		
ss_sync_req_tag	24	uimsbf
length_field()=0		
}		

Figure 22: ss_sync_req APDU syntax

ss_sync_req_tag:0x9F 90 05.

2) ss_sync_cnf APDU

This APDU is the response of the master client to the ss_sync_req APDU, indicating that the master client has completed the key calculation. The syntax of the ss_sync_cnf APDU is shown in Figure 23.

syntax	No. of bits	Mnemonic
ss_sync_cnf() {		
ss_sync_cnf_tag	24	uimsbf
length_field()=0		
status_field	8	uimsbf
}		

Figure 23: ss_sync_cnf APDU syntax

ss_sync_cnf_tag: 0x9F 90 06.

status_field: This byte returns the status of the master client. Figure 24 lists possible values.

status_field	value
OK	00
No resource	01
Busy	02
Authentication failure	03
Reserved	04-FF

Figure 24: Possible values of status_field

The APDU format of the SAC initialization protocol, which includes specific data types, is shown as below:

When the slave server sends SERVER_ID and a random number, ss_data_req APDU is sent with following Parameters in Figure 25.

content		
send _datatype_nbr=2		
i	datatype_id	datatype_len
0	2(SERVER_ID)	64 bits
1	16(Ns_M)	64 bits
request_datatype_nbr=2		
i	datatype_id	
0	1(CLIENT_ID)	
1	15(Ns_H)	

Figure 25: ss_data_req APDU content

When the master client responds with CLIENT_ID and a random number, ss_data_cnf APDU is sent with following Parameters in Figure 26.

content		
send _datatype_nbr=2		
i	datatype_id	datatype_len
0	1(CLIENT_ID)	64 bits
1	15(Ns_H)	64 bits

Figure 26: ss_data_cnf APDU content

Note: During the secure channel establishment phase, APDU messages will encapsulate the Modbus serial link data unit field with a success code of 0, which is much smaller than 252 bytes (the maximum data field length of a Modbus RTU frame) of APDU. One Modbus serial link message frame can complete the interaction of APDU.

The operation process of the master client during SAC initialization is shown as below.

1. Master client receives “Ns_M”.

2. Master client sends “Ns_H”.

3. Master clientcalculates SAK and SEK.

4. Master client receives synchronization request.

5. Master client confirms synchronization and starts using the new SAC key

The operation process of the slave server during SAC initialization is shown as below.Note: If the condition in step 6 (or step 9) is not met more than 3 times, it will result in a system error.

1. Start SAC initialization.

2. Set the SAC key update timer to 0 seconds on the slave server.

3. Slave server sends ’Ns_M’.

4. Slave server receives ’Ns_H’.

5. Slave server calculates SAK and SEK.

6. SAC key update timer is more than 9s and allow SAC to reinitialize? If Yes, goto step 1).

7. If not, Slave server sends sync request.

8. Slave server received sync confirmation within 10s?

9. If not, Key update timer is more than 10s and allow SAC to reinitialize? If yes, goto step 1).

10. If not, Wait for 1 second, goto step 7).

11. Slave server allows SAC operations.

12. Set message counter msg_counter = 1 on the slave server

13. Any messages need to be sent? If not, goto step 13).

14. If yes, msg_counter is overflow and allow SAC to reinitialize? If yes,goto step 1).

15. If not, send a message from the slave server and add msg_counter + 1, goto step 13).

Calculating the authentication key SAK and encryption key SEK for SAC requires two steps:

1. Calculation of key seed Ks.

2. Export SAK and SEK.

The key seed Ks has a length of 256 bits. The slave server and master client should calculate the value of the key seed, and the master client must use the following method to calculate Ks_client:

Ks_client = SM3(DHSK||AKH||Ns_H||Ns_M)

The slave server must calculate Ks_server using the following method:

Ks_server = SM3(DHSK||AKM||Ns_H||Ns_M)

Under normal circumstances, Ks_server = Ks_client, this two keys herein are named Ks, with the parameters shown in Figure 27

parameter	No. of bits
DHSK	512
AKH/AKM	256
Ns_H	64
Ns_M	64

Figure 27: Parameters in SAC Key Calculation

The SAK and SEK exports are calculated as follows:

SEK=MSB128(Ks), SAK=LSB128(Ks)

The SAC message format and semantic description are as follows:

The data messages transmitted as SAC payloads should be encapsulated in SAC messages, with the encapsulation format shown in Figure 28.

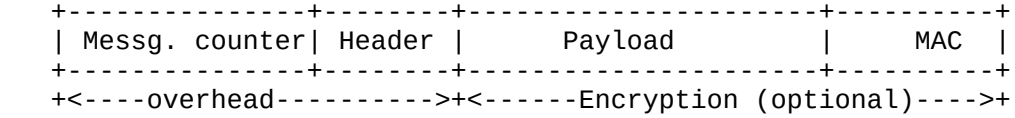


Figure 28: SAC packaging payload

The specific definition of SAC message syntax is shown in Figure 29.

syntax	No. of bits	Mnemonic
message() {		
message_counter	32	uimsbf
/* Message header start */		
protocol_version	4	uimsbf
authentication_cipher_flag	3	uimsbf
payload_encryption_flag	1	bslbf
encryption_cipher_flag	3	uimsbf
reserved_for_future_use	5	bslbf
length_payload	16	uimsbf
/* Message header end */		
/* Message body start */		
if (payload_encryption_flag == MSG_FLAG_TRUE) {		
encrypted_payload	length_payload * 8+128	bslbf
}elif (payload_encryption_flag == MSG_FLAG_FALSE) {		
payload	length_payload * 8	bslbf
authentication	128	bslbf
}		
/* Message body end */		
}		

Figure 29: SAC message syntax

Encoding and semantics of fields in SAC messages:

1. message_comounter: Data messages require a count value to identify the number of messages that have been transmitted.

2. protocol version: In this section, set to 0x0.

3. authentication_cipher_flag: This parameter specifies the algorithm that generates the authentication code, currently only 0x0 is valid, means AES-128-XCBC-MAC, other values are reserved.

4. payload_decryption-flag: This parameter indicates whether the payload is encrypted. ’1’ indicates encryption, ’0’ indicates no encryption. Devices that comply with this section are explained as "1" and other unsupported values are ignored.

5. encryption_cipher_flag: This parameter indicates the encryption algorithm, currently only 0x0 is valid, means AES-128, CBC mode, other values are reserved.

6. length_payload: This parameter represents the number of bytes in the payload, including padding data but not the number of bytes in the authentication code.

7. encrypted_payload: This field consists of encrypted data, including ciphertext for message payload, padding data, and authentication code.

8. payload: This field is composed of unencrypted data.

9. authentication: This field carries the authentication code for the data, which can be encrypted according to the indication of "payload_encryption_flag".

The data message submitted for SAC transmission when sending SAC messages should be processed according to the following steps:

1. Check if ’message_counter’ overflows and update ’message_counter’.

2. Calculate the message authentication code.

3. If encryption is required, concatenate the authentication code and payload to encrypt the message (optional).

4. Construct SAC messages.

5. Transmitting messages.

If any step of the above process fails, the message and status (such as key set, counter, etc.) should be destroyed and an error generated.

The authentication code for SAC data messages is calculated as follows:

authentication =
MAC{SAK}(length(header_hi)||i||header_hi||payload_pi)

Where:

1. MAC - The algorithm is identified by "authentication_cipher_flag";

2. SAK - is a 128 bit SAC authentication key;

Authentication code calculation is specific to the entire message, with parameters shown in Figure 30.

Parameter	No. of bits	Mnemonic
length_hi	8	uimsbf
i	32	uimsbf
header_hi	length_hi * 8	bslbf
payload_pi	length_payload*8	bslbf

Figure 30: Parameters in MAC Calculation

1. i: This field is the ’message_counter’ in the data message.

2. length_hi: This field is the number of bytes in the message header.

3. header_hi: This field represents the message header.

4. d) payload_pi: This domain carries the message payload. The original unencrypted payload.

If SAC messages need to be encrypted, the following method should be used:

encrypted_payloadi = E{SEK, SIV}(payload_pi||authentication_ai)

Where:

1. E - The encryption algorithm indicated by encryption_cipher_flag;

2. SEK -128 bit encryption key;

3. SIV - a fixed constant with a value of 0xB27097DEAF305D8A94C871D89525C7A0;

4. authentication_ai - This value is the authentication code MAC.

If the length of payload_pi is not an integer multiple of 128 bits, it should be padded with a "1" first, followed by several "0s" so that the padded result is an integer multiple of 128 bits. If the payload is not encrypted, it will not be filled.

SAC message reception should be processed according to the following steps:

1. Firstly, check if the message contains the correct "message_counter" and "protocol-version";

2. If ’payload_encryption-flag’=1, decrypt the message payload;

3. Calculate the message authentication code and verify the integrity of the message.

If any step of the above process fails, the message and status (such as the key set, counter, etc.) should be destroyed and an error should be generated.

Both the slave server and the master client should maintain a message counter (message_counter) locally to identify the number of messages that have been transmitted. The initial value of this counter is 0x01 (not 0x00), and every time a SAC message is sent or received, the counter value is incremented by 1. In the current counter value state, if a message needs to be sent, assign the current value of the counter to the "message_counter" field in the SAC message being sent. After the message is sent, increment the counter value by 1. In the current counter value state, if a message is received, the value of the "message_counter" field in the received SAC message should be the same as the current value of the counter. After receiving the message, the counter value needs to be incremented by 1. The receiving device should not receive messages with incorrect counter values. Incorrect counter values will result in a ’message sequence error’. When the value of the message sending counter of the slave server overflows (reaching 232), the slave server should stop using the current SAC key and start negotiating a new SAC key.

The decryption process of SAC data messages is as follows:

payload_pi || authentication_ai = D{ SEK, SIV}(encrypted_payloadi)

Where:

1. D - the algorithm indicated by "encryption_cipher_flag";

2. SEK -128 bit key;

3. SIV - a fixed constant with a value of 0xB27097DEAF305D8A94C871D89525C7A0;

Among them, ’authentication_ai’ should be separated from ’payload_pi’. If ’payload_pi’ is not an integer multiple of the 128 bit packet, then the message is obtained by padding a ’1’ and several ’0s’. If the payload is not encrypted, there is no need to fill in any data.

The SAC data message contains an authentication domain, and its verification process is as follows:

authentication_ai’ =
MAC{SAK}(length(header_hi)||i||header_hi||payload_pi)

Where:

1. MAC - The algorithm is identified by "authentication_cipher_flag";

2. SAK -128 bit SAC authentication key.

If the calculated ’authentication_ai’ is not equal to the ’authentication_ai’ exported from the message, the received message must be deleted and a ’message validation error’ generated.

Note: The design of SAC channels can be used for various purposes, mainly for negotiating and updating content keys. The way SAC messages are encapsulated into Modbus serial link data unit fields with function code 0 in Figure 31. The packaging steps is given as follows Since SAC is mainly used to synchronize and update CK content key data in this specification, as detailed in the next chapter, one Modbus serial link data unit can be sent completely in one message.

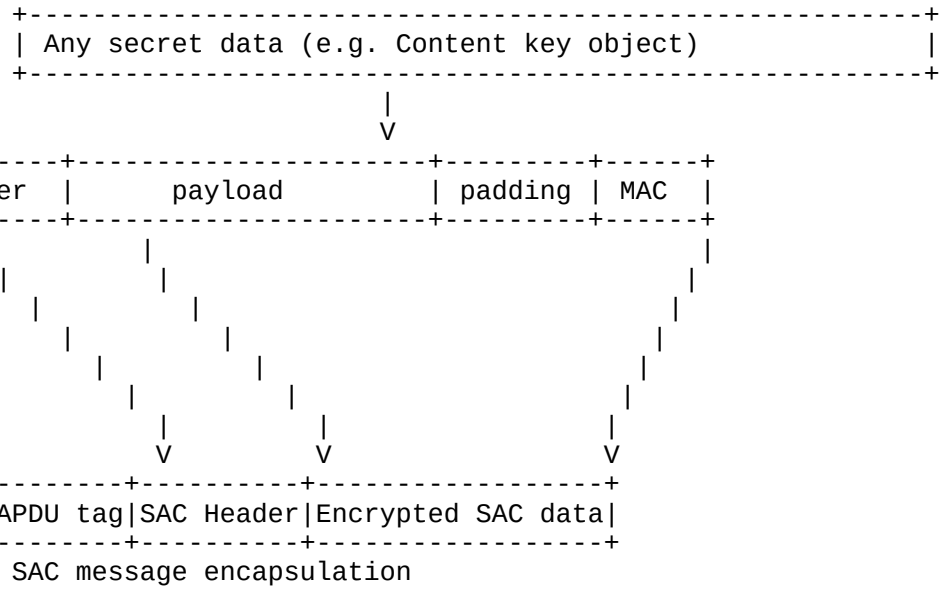


Figure 31: SAC message encapsulation

1. The system collects data objects to form SAC payloads

2. System calculates message authentication code

3. The SAC payload and authentication code are encrypted. Add SAC header, APDU tag, and APDU length field before the encrypted SAC data

5.2.2.4. Content Key Update Mechanism

The process of the content key CK update protocol is shown in Figure 32, and the its description is shown as follows

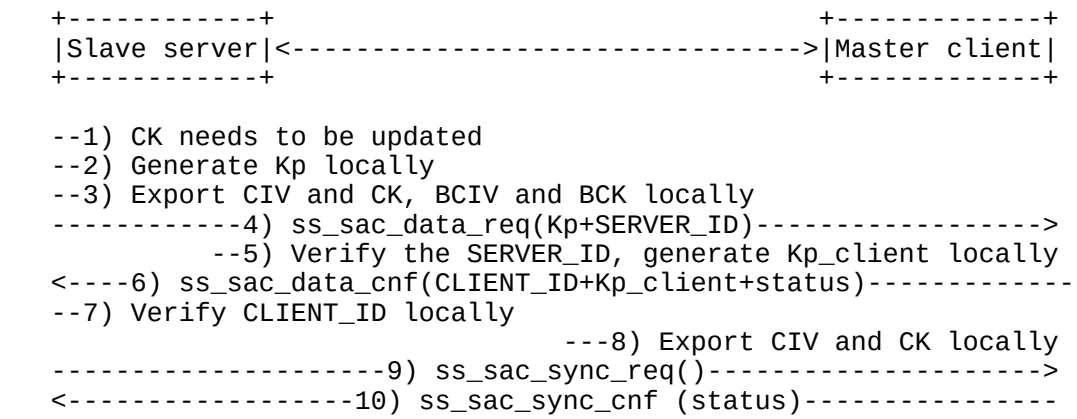


Figure 32: The CK Content Key Update Process

1. When the slave server detects the need for CK update, the slave server begins the CK update process.

2. The slave server generates a 256 bit nonce and calculates Kp=SM3 (nonce).

3. The slave server can immediately start calculating CIV and CK.

4. The slave server sends an ss_sac_data_req APDU containing the following parameters： 1) Kp； 2) SERVER_ID；

5. The master client checks that the received SERVER_ID matches the one in "authentication context". If they are consistent, the master client starts calculating CIV and CK, BCIV and BCK; If there is inconsistency, it will result in a system error. Note: The pre stored SERVER_ID/CLIENT_ID is in the "authentication context".

6. The master client generates a 256 bit nonce and calculates Kp_client = SM3 (nonce). Respond to ab ss_sac_data_cnf APDU containing CLIENT_ID and Kp_client. Failure to respond to this message will result in a system error.

7. The slave server checks that the received CLIENT_ID matches the one in "authentication context". If they are consistent, the slave server starts calculating CIV and CK; If there is inconsistency, it will result in a system error. Note: The pre stored SERVER_ID/CLIENT_ID is in the "authentication context".

8. The master client calculates CIV and CK, while the slave server calculates BCIV and BCK.

9. The slave server sends an ss_sac_sync_req APDU to the master client to indicate content key updates. When the slave server completes the initialization of the encryption process, it sends a synchronization request to the master client, informing them that the slave server is ready to use the new CK and BCK.

10. The master client responds with an ss_stac_sync_cnf APDU and confirms to the slave server that the master client is also ready to use the new CK and BCK. Failure to respond to this message will result in a system error.

The update of content key CK is mainly initiated by the slave server, and the master client only passively responds. This process is optional, and the content key CK update protocol is triggered by any of the following conditions:

1. After successful completion of authentication and SAC initialization.

2. Periodic triggering (maximum key lifecycle parameter, configured by administrator).

3. The block counter has reached its upper limit.

4. Every time it restarts.

5. System allows SAC to reinitialize.

APDU definition used in the content key update protocol process:

1) ss_sac_data_req APDU

The slave server uses this APDU to send protocol specific data to the master client, while requesting a response. The syntax of ss_sac_data_req APDU is shown in Table 25. Unlike ss_data_req APDU, the data contained in this message is authenticated and encrypted. SAC uses the input data in Figure 33 as the payload in the SAC message.

syntax	No. of bits	Mnemonic
ss_sac_data_req() {		
ss_sac_data_req_tag	24	uimsbf
length_field()=0		
sac_message()		
}		

Figure 33: ss_stac_data_req APDU syntax

ss_sac_data_req_tag: 0x9F 90 07.

sac_message: The format of this message was defined in the previous section,payload_encryption-flag should be 1.

The definition of the payload of SAC messages is in Figure 34.

syntax	No. of bits	Mnemonic
ss_system_id_bitmask	8	bslbf
send_datatype_nbr	8	uimsbf
for (i=0;i<send_datatype_nbr; i++) {		
datatype_id	8	uimsbf
datatype_length	16	uimsbf
data_type	8*datatype_length	bslbf
}		
request_datatype_nbr	8	uimsbf
for (i=0; i<request_datatype_nbr; i++){		
datatype_id	8	uimsbf
}		
}		

Figure 34: ss_sac_data_req Payload syntax

ss_system_id_bitmask: Same as above.

send_datatype_nbr: This message contains the number of data categories.

datatype_id: See Appendix A.

datatype_length: The byte length of the data in the form of a data type.

data_type: The specific data represented by datatype_id.

request_datatype_nbr: The number of data categories that the primary client should include in its response.

datatype_id: See Appendix A.

2) ss_sac_data_cnf APDU

When data needs to be authenticated and encrypted, the master client should use this APDU to send protocol specific data to the slave server. The syntax of ss_sac_data_cnf APDU is shown in Figure 35. The input data in SAC encapsulation in Figure 36 is used as the payload in the SAC message.

syntax	No. of bits	Mnemonic
ss_sac_data_cnf() {		
ss_sac_data_cnf_tag	24	uimsbf
length_field()=0		
sac_message()		
}		

Figure 35: ss_sac_data_cnf APDU syntax

syntax	No. of bits	Mnemonic
ss_system_id_bitmask	8	bslbf
send_datatype_nbr	8	uimsbf
for (i=0;i<send_datatype_nbr; i++) {		
datatype_id	8	uimsbf
datatype_length	16	uimsbf
data_type	8*datatype_length	bslbf
}		

Figure 36: ss_sac_data_cnf Payload syntax

ss_system_id_bitmask: Same as above.

send_datatype_nbr: This message contains the number of data categories.

datatype_id: See Appendix A.

datatype_length: The byte length of the data in the form of a data type.

data_type: The specific data represented by datatype_id.

3) ss_sac_sync_req APDU

This APDU is used in the CK calculation process. The slave server sends this message to indicate that it has completed the new CK calculation. The syntax of ss_sac_sync_req APDU is shown in Figure 37.

syntax	No. of bits	Mnemonic
ss_sac_sync_req() {		
ss_sac_sync_req_tag	24	uimsbf
length_field()=0		
sac_message()		
}		

Figure 37: ss_stac_sync_req APDU syntax

ss_sac_sync_req_tag: 0x9F 90 09.

sac_message: Same as above.payload_encryption_flag should be 1.The payload of the SAC message here is empty.

4) ss_sac_sync_cnf APDU

This APDU is used in the CK calculation process. The master client responds with this message to the ss_sac_sync_req APDU message sent from the slave server. The syntax of the ss_sac_sync_cnf APDU is shown in Figure 38.

syntax	No. of bits	Mnemonic
ss_sac_sync_cnf() {		
ss_sac_sync_cnf_tag	24	uimsbf
length_field()=0		
sac_message()		
}		

Figure 38: ss_sac_sync_cnf APDU syntax

ss_sac_sync_req_tag: 0x9F 90 10.

sac_message: Same as above.payload_encryption_flag should be 1.The payload of this SAC message is a state domain. All possible values in the state domain are listed in Figure 39.

status_field	value
OK	00
No resource	01
Master client busy	02
Not required	03
Reserved	04-FF

Figure 39: State Fields in ss_sac_sync_cnf

When sending SERVER_ID and a random number from the slave server, ss_sac_data_req APDU is sent with following Parameters in Figure 40.

content		
send _datatype_nbr=2		
i	datatype_id	datatype_len
0	2(SERVER_ID)	64 bits
1	7(Kp)	256 bits
request_datatype_nbr=2		
i	datatype_id	
0	1(CLIENT_ID)	
1	20(Status_field)	

Figure 40: ss_sac_data_req APDU content

When the master client responds with CLIENT_ID and status information, ss_sac_data_cnf APDU is sent with following Parameters in Figure 41.

content		
send _datatype_nbr=3		
i	datatype_id	datatype_len
0	2(SERVER_ID)	64 bits
1	7(Kp_client)	256 bits
2	20(Status_field)	8 bits

Figure 41: ss_sac_data_cnf APDU content

The CK update operation on the slave server side is shown as below, and the broadcast content key BCK can be generated along with it.

1. CK update begins

2. Set CK update timer to 0s on the slave server

3. Send Kp

4. Calculate CIV and CK, BCIV and BCK.

5. Receive responses from the master client.

6. Is the initial key lifecycle? If not, goto step 12).

7. If yes, Timer is more than 9s and allow SAC to reinitialize? If yes, goto step 21).

8. If not, Send sync request

9. sync confirm within the valid time? If yes, goto step 17)

10. Timer is more than 10s and allow SAC to reinitialize? If yes, goto step 21)

11. Wait for 1s,goto step 8).

12. Timer is more than 9s? if not, goto step 12)

13. Send sync request

14. Received sync confirmation? if yes, goto step 17)

15. Counter: 30>t>10? if yes, goto step 17), if t is not more than 10s, goto step 14)

16. Allow SAC to reinitialize? if yes, goto step 1)

17. Stop receiving data, goto step 14)

18. Slave server can receive data.

19. Set the block counter to 1.

20. Key lifetime exhausted and allow SAC to reinitialize? if yes, goto step 1)

21. block counter overflow and allow SAC to reinitialize? if yes, goto step 1) else got step 20)

Note: The key update timer is used to record the calculation time of the new CK.

Note: The maximum key lifecycle value is controlled by the administrator configuration system and is not within the scope specified in this specification. The decrease of this value is controlled by the slave server and only decreases when encrypting or

decrypting content. For ease of processing, it is generally defined by the number of messages. So when CK is not in use, this value is not updated. Note: The default upper limit of the block counter is 232, and the message may be divided into multiple block frames. The CK block counter limit is the number of processed crypto blocks since CK refresh. The number of block limit defined here is configured by the system and is not within specified in this specification.

Note: The initial key lifecycle refers to the first key lifecycle after SAC initialization.

The CK update operation on the master client side is shown as below, and the broadcast content key BCK can be generated along with it.

1. Waiting for the key update from the slave server.

2. Receive Kp.

3. Confirm.

4. Calculate CIV and CK, BCK and CIV.

5. Receive sync request.

6. Confirm the sync request and start using the new CK.

The calculation process of content key CK and broadcast content key BCK should be completed as follows:

The encryption algorithm requires CK and CIV, and the calculation of these two values requires two steps: key seed calculation and CK and CIV export.

Step 1: Calculate the key seed.

Kp = SM3(nonce)

Step 2: Export CK and CIV.

CK = MSB128(SM3(Kp||SERVER_ID)), CIV = LSB128(SM3(Kp||SERVER_ID))

Step 3: Export BCK and CIV for broadcast communication between the master client and all slave servers.

BCK = MSB128(SM3(Kp_client||CLIENT_ID)), BCIV = LSB128(SM3(Kp_client||CLIENT_ID))

Where:

SERVER_ID represents the ID of the slave server, while CLIENT_ID represents the ID of the master client. CIV remains unchanged throughout each key lifecycle. CIV and CK change simultaneously. The current CIV is reused at the beginning of encrypting (decrypting) each Modbus data frame. During broadcast communication, BCK and BCIV should be changed simultaneously. Generally, after power on, the BCK and BCIV of all slave servers can remain unchanged, or they can be updated by the master station through the SAC content key update protocol. The process of updating BCK protocol is shown as follows separately.

1. The master client generates a 256 bit nonce and calculates Kp_client=SM3 (nonce).

2. The master client can immediately start calculating BCIV and BCK..

3. The master client sends an ss_sac_data_req APDU containing the following parameters to the slave server: 1) Kp_client ; 2) CLIENT_ID ;

4. The slave server checks the consistency between the received CLIENT_ID and the "authentication context". If they are consistent, calculate BCIV and BCK from the site server; If there is inconsistency, it will result in a system error. Note: The pre-stored SERVER_ID/CLIENT_ID is in the "authentication context".

5. The slave server responds with an ss_sac_data_cnf APDU containing the SERVER_ID. Failure to respond to messages will result in a system error.

6. The master client checks that the received SERVER ID matches the ’authentication context’. If the SERVER_ID returned by the main client is incorrect, a system error will be returned.

7. The master client sends an ss_sac_sync_deq APDU to indicate BCK updates. When the slave server completes the initialization of the encryption process, it sends a synchronization request to the master client, informing them that the slave server is ready to use the new CK and BCK.

8. The slave server responds with the ss_sac_sync_cnf APDU and confirms to the slave server that the master client is also ready to use the new CK and BCK. Failure to respond to this message will result in a system error.

The APDU format of the protocol that includes specific data types during the separate update process of BCK broadcast content keys is shown in Figure 42 below:

When the master client sends a CLIENT_ID and a random number to the slave server, ss_sac_data_req APDU is sent with following Parameters in Figure 42.

content		
send _datatype_nbr=2		
i	datatype_id	datatype_len
0	2(CLIENT_ID)	64 bits
1	7(Kp_client)	256 bits
request_datatype_nbr=2		
i	datatype_id	
0	1(SERVER_ID)	
1	20(Status_field)	

Figure 42: ss_sac_data_req APDU content

When the slave server responds with the SERVER_ID and status information, ss_sac_data_cnf APDU is sent with following Parameters in Figure 43.

content		
send _datatype_nbr=2		
i	datatype_id	datatype_len
0	1(SERVER_ID)	64 bits
1	20(Status_field)	8 bits

Figure 43: ss_sac_data_cnf APDU content

Note: During the content key update phase, APDU messages will encapsulate the Modbus serial link data unit field with function code 0, which is much smaller than 252 bytes (the maximum data field length of a Modbus RTU frame) of APDU. One Modbus serial link message frame can complete the interaction of APDU.

5.2.2.5. Content Encryption and Decryption Mechanism

After the authentication channel is established and the content keys BCK and CK are synchronized, when transmitting the encrypted Modbus serial link protocol, the encrypted content includes the original Modbus serial link protocol function code and data fields. The encryption mechanism for unicast and broadcast is the same, only the key parameters are different. The content encryption method varies depending on the synchronous encryption and decryption method. This draft document supports AES GCM and SM4 GCM mode encryption algorithms, 128-EEA3/128-EIA3 encryption algorithms based on ZUC, and ChaCha20-Poly1305 encryption algorithms for reference implementation.

1. In AES GCM and SM4 GCM mode encryption, taking unicast communication as an example, the content encryption method has the following input parameters: CIV, CK, Mode, Modbus serial link protocol function code and data. Among them, CIV and CK are secret data shared by the master client and slave server after executing the content key update protocol. CIV is the CTR in the algorithm, CK is the content key, and Mode is the encryption and decryption mode agreed upon by both parties during the first binding. mode = aes_gcm or sm4_gcm, indicated by the "encryption_capability" field in the device’s public key certificate. The plaintext are sliced in 128 bit block of data from the function and data fields in the original Modbus PDU, and those that are less than 128 bits long are filled with 0 to be 128 bit integers, with associated data taken from the first 128 bits of SM3 (“Modbus”).

2. In 128-EEA3/128-EIA3 encryption algorithm based on ZUC, the 128-EEA3/128-EIA3 encryption algorithm based on ZUC can be found in the standards ETSI/SAGE TS35.221 and ETSI/SAGE TS35.222. In this mode, the mode field corresponds to mode=zuc. The data in the original Modbus PDU is concatenated with the function and data fields and sliced into 128 bit slices. If it is not 128 bits long enough, it is filled with 0 to a 128 bit integer. Assuming that the filled data is M and the total length is MPLEN. CIV and CK are secret data shared between the master client and slave server after executing the content key update protocol. The parameter initialization corresponds to the following Figure 44:

3. In ChaCha20-Poly1305 encryption algorithm.The ChaCha20-Poly1305 encryption algorithm can be found in RFC 8439. In this mode, the mode field corresponds to mode = chapoly. The data in the original Modbus PDU is concatenated with the function and data fields and sliced into 512 bit slices. If the length of slice is less than 512 bits, it is filled with 0 to a 512 bit integer. CIV and CK are secret data shared between the master client and slave server after executing the content key update protocol. The initial counter of the algorithm in this draft document defaults to 0. The 256-bit encryption key, 96-bit the random number and additional data are generated as follows: Chapoly_key = CK||CK (duplication), Nonce = MSB96(CIV), associated_data= LSB32(CIV), ChaCha20-Poly1305 generates a 128 bit MAC while encrypting.

Parameter	No. of bits	Value	description
COUNT	32	MSB32(CIV)	counter
BEARER	5	00000	Bearing layer ID
DIRECTION	1	0	Transmission direction
CK	128	CK	Confidentiality Key
IK	128	CK	Integrity key
LENGTH	32	MPLEN	Bit length of message
IBS	LENGTH	M	Message

Figure 44: 128-EEA3/128-EIA3 Parameter Initialization

The encrypted Modbus security protocol data field content should be transmitted in the following APDU format, with the encapsulation method shown in Figure 45. The implementation principle of ASCII transmission mode is similar, and not repeated here:

The data content of Modbus security protocol is sent through ss_data_snd APDU, and the cotent syntax of ss_data_snd APDU is shown in Figure 46.

syntax	No. of bits	Mnemonic
ss_data_send() {		
ss_data_send_tag	24	uimsbf
length_field()	8	
MAC	128	bslbf
encrypted_fun_code_data	8*length	bslbf
}		

Figure 45: ss_data_snd APDU syntax

ss_open_send_tag: 0x9F 90 11.

MAC: Message authentication code, if less than 128 bits, add 0, for example 128-EIA3 only outputs 32-bit MAC.

encrypted_fun_comde_data: encrypted Modbus serial link protocol function codes and data.

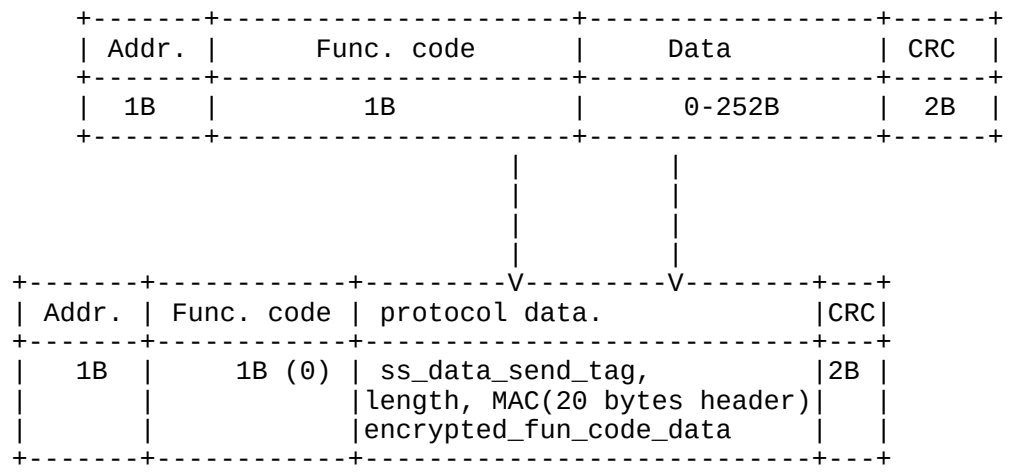


Figure 46: Modbus encrypted content encapsulation

5.2.3. Modbus Serial Link Security Protocol Based on Password or Pre-Shared Key

The key management in the Modbus serial link security protocol based on passwords or pre-shared keys relies on hardware protection. The goal of the protocol is to provide strong security on the basis of low entropy passwords, allowing master-slave devices to negotiate and obtain the same content key while resisting command or key guessing attacks. This type of protocol is suitable for use in factories and equipment with general value and security. The pre-shared key or password requires a trusted and secure execution environment protection, which shall ensure the security of user passwords or shared keys during device operation and prevent them from being stolen by malicious third parties. This model is relatively simple and can be divided into three levels: password or shared key storage level, authentication level, and content encryption level.

5.2.3.1. Key hierarchy structure

The password or pre-shared key storage hierarchy should include protocol public parameters, pre shared passwords or keys for the master client and slave server. The key data at this level is mainly used to execute authentication protocols. The pre-shared keys after device initialization cannot be changed or replaced, nor can they be obtained by unauthorized users. The definition of protection methods for these data is not within the scope of this specification.

At the authentication level, the master client and slave server mainly verify each other’s identity through cryptographic protocols based on shared passwords or keys, and generate temporary content keys CK and an initial vector CIV for use by the content encryption layer. For the generated intermediate keys or state values, there should be a trusted execution environment to ensure security. The protection methods for these intermediate keys or state values are not within the scope of this specification. In password or pre-shared key based schemes, each party in the master-slave device combines its own password or pre shared key based value and private key with the other party’s public key to obtain one or more identical keys. Other (public or private) information known to both the master and slave devices can also be used as key derivation parameters to participate in content key generation. If all parties use the same password or pre shared key and the same key derivation parameters, the protocol will ensure that all parties will receive the same content key, allowing both parties to export the shared key with only the password or pre shared key. It should be ensured that without using the password or pre shared key, neither party can successfully participate in the protocol and obtain the same content key.

The content encryption layer uses the content key CK and an initial vector CIV to encrypt and decrypt the media stream using AES/SM4. For the data encryption and decryption process of Modbus serial link communication protocol, there should be a trusted execution environment or hardware to ensure security. The definition of specific protection methods is not within the scope of this specification.

5.2.3.2. Authentication and Key Agreement Mechanism

This specification is based on the Modbus serial link security protocol using passwords or pre shared keys, and is based on the SM2 elliptic curve public key cryptography algorithm Part 3 Key Exchange Protocol standard developed by ISO/IEC 14888-3:2018 and China National Cryptography Administration. In this specification, the private key of the master and slave devices should be derived from a shared password or key. Assuming that the password or key shared by

the master/slave devices is represented as PW, the temporary private key of the device must be generated as follows:

The master/slave devices first respectively select a random number r and calculate the 32-bit byte string PW_r=SM3 (PW||r). By converting it into an element under the field F_q of ECC, the private key d_A is obtained, and the public key P_A=[d_A] G=(x_A, y_A) is calculated. Assuming that the public and private key pairs of the master/slave devices are d_H/P_H, d_M/P_M, respectively.

The authentication and content key negotiation mechanism is shown as below. For master client, the raw data generated and configured by the host client are (ECC system parameters, Z_H, Z_M, d_H, P_H, P_M) and a 128bit random number r_nonce is selected to generate the broadcast key and encryption/decryption mode.

1. Generate random number r_H ∈ [1, n-1].

2. Calculate R_H=[r_H] G=(x_1, y_1).

3. Send R_H, mode to the slave server.

4. Calculate X_1=2^w+(X_1 AND(2^w-1)).

5. Calculate t_H= (d_H+X_1*r_H) Mod n.

6. Receivce R_M, S_M from the slave server, does R_M satisfy the curve equation? If not, Content key negotiation failed.

7. Calculate X_2=2^w+(x_2 AND (2^w-1)).

8. Calculate ECC pointU = [h*t_H](P_M+[X_2]R_M)=(x_u,y_u).

9. U=O? If yes, Content key negotiation failed.

10. Calculate K_H=KDF(PW||x_u||y_u||Z_H||Z_M,256).

11. Calculate S_1=SM3(0x02||PW||y_u||Hash(x_u||Z_H||Z_M||x_1||y_1||x_2||y_2||||r_B)).

12. S_1=S_M? If not, Content key negotiation failed.

13. Calculate S_H=SM3(0x03||PW||y_u||Hash(x_u||Z_H||Z_M||x_1||y_1||x_2||y_2)||r_B), r_B=MSB128(K_H)r_nonce, Sends S_H, r_B to Slave server.

14. Calculate CK=MSB128(K_H), CIV=LSB128(K_H).

15. Calculate BCK=MSB128(SM3(r_nonce||PW)), BCIV=LSB128(SM3(r_nonce||PW)).

For slave server, the raw data generated and configured are (elliptic curve system parameters, Z_H, Z_M, d_M, P_M, P_H).

1. Generate random number r_M ∈ [1, n-1].

2. Calculate R_M=[r_M] G=(x_2, y_2).

3. Take X_2=2 ^ w+(x_2 AND (2 ^ w-1)).

4. Calculate t_M=(d_M+X_2 * r_M) mod n.

5. Receivce R_H, mode from the slave server, Does R_H satisfy the curve equation? If not, Content key negotiation failed.

6. Calculate X_1=2^w+(x_1 AND (2^w-1)).

7. Calculate ECC point V = [h*t_M](P_H+[X_1]R_H)=(x_v,y_v).

8. V=O？ If yes, Content key negotiation failed.

9. Calculate K_M=KDF(PW||x_v||y_v||Z_H||Z_M,256).

10. Calculate S_M=SM3(0x02||PW||y_v||Hash(x_v||Z_H||Z_M||x_1||y_1||x_2||y_2||||r_B)).

11. Sends R_M、S_B to Master client.

12. Calculate S_2=SM3(0x03||PW||y_v||Hash(x_v||Z_H||Z_M||x_1||y_1||x_2||y_2||r_B)).

13. Receive S_H, r_B from the master client,S_2=S_H？ If not, Content key negotiation failed.

14. The CK confirmation from the Master client to the slave server has been successful, Calculate CK=MSB128(K_M),CIV=LSB128(K_M), r_nonce=MSB128(K_M)r_B, BCK=MSB128(SM3(r_nonce||PW)), BCIV=LSB128(SM3(r_nonce||PW)).

The encryption algorithm mode is determined by an 8-bit mode and supports AES GCM mode aes_gcm, SM4 GCM mode sm4_gcm, zuc mode and chapoly mode.

The steps of Modbus serial link security protocol based on password or pre-shared key are shown in Figure 47 and described as below:

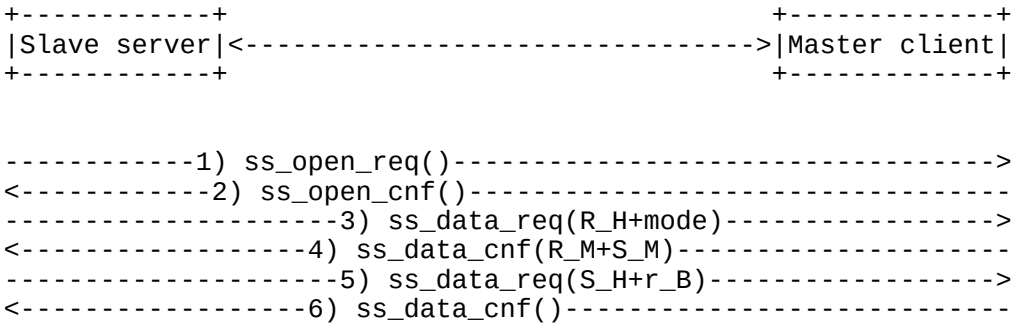


Figure 47: Content key negotiation message exchange based on password or pre-shared key

1. The master client sends the ss_sk_open_req APDU to the slave server.

2. The slave server responds with ss_sk_open_cnf APDU.

3. The master client sends the ss_sk_data_req APDU to the slave server. The message contains: 1) The master client selects the ECC point (R_H) as needed; 2) Encryption and decryption mode; 3) The ID of the requested data type.

4. The slave server responds with ss_sk_data_cnf APDU. The message contains: 1) The slave server selects ECC points (R_M) as needed; 2) Message authentication code (S_M) of the slave server; Failure to respond to this message may result in a system error, possibly due to the master client being unable to verify data from the slave server.

5. The master client then sends the ss_sk_data_req APDU. The message contains: 1) The message authentication code (S_H) of the master client; 2) Random number (r_B) used to generate broadcast content keys ; Failure to respond to this message may result in a system error, possibly due to the slave server being unable to verify data from the master client.

6. The slave server responds with ss_sk_data_cnf APDU. The inability to respond to this message may result in a system error, possibly due to the inability of the master client to verify data from the slave server.

The format definitions of ss_sk_open_req, ss_sk_open_cnf, ss_sk_data_req, and ss_sk_data_cnf APDU are the same as those of the previous ss_open_req, ss_open_cnf, ss_data_req, and ss_data_cnf APDU, respectively. But the tag types are different to distinguish different serial link content encryption mechanisms.

ss_sk_open_req(tag=0x9F 90 12), ss_sk_open_cnf(tag=0x9F 90 13), ss_sk_data_req(tag=0x9F 90 14), ss_sk_data_cnf(tag=0x9F 90 15), The APDU format for protocols based on passwords or pre-shared keys that include specific data types is shown as below:

When the master client sends a ECC random point, a random number, and encryption/decryption mode to the slave server, ss_sk_data_req APDU is sent with following Parameters in Figure 48.

content		
send _datatype_nbr=2		
i	datatype_id	datatype_len
0	22(R_H)	512 bits
1	24(mode)	8 bits
request_datatype_nbr=2		
i	datatype_id	
0	22(R_M)	
1	25(S_M)	

Figure 48: ss_sk_data_req APDU content

When sending response ECC random point and authentication code from the slave server, ss_sk_data_cnf APDU is sent with following Parameters in Figure 49.

content		
send _datatype_nbr=2		
i	datatype_id	datatype_len
0	22(R_M)	512 bits
1	25(S_M)	256 bits

Figure 49: ss_sk_data_cnf APDU content

When the master client sends a message authentication code, ss_sk_data_req APDU is sent with following Parameters in Figure 50.

content		
send _datatype_nbr=2		
i	datatype_id	datatype_len
0	9(S_H)	256 bits
1	23(r_B)	256 bits

Figure 50: ss_sk_data_req APDU content

5.2.3.3. Content Encryption and Decryption Mechanism

The content encryption and decryption mechanism used in this section is the same as that in previous section.

5.2.4. Modbus Serial Link Security Protocol Based on Post Quantum Hybrid Signature Public Key Certificate

5.2.4.1. Key hierarchy structure

The key management in Modbus serial link security protocol based on post quantum hybrid signature public key certificate is suitable for future high-value and high security factory equipment environments. It smoothly transitions with existing standards and is divided into three levels: certificate storage level, authentication and key negotiation level, and content encryption and decryption level. The certificate fields and contents are shown in Appendix C. Compared with the paramters contained in "Modbus Serial Link Security Protocol Based on ECC Public Key Certificate", The following list supplements the main parameter names, storage, and usage of the post quantum algorithm involved in the post quantum hybrid signature public key certificate.

1. Root certificate: Certificate of system trust root, which is non-volatile storaged and local use.

2. Brand certificate: Brand certificate of device manufacturer, which is non-volatile storaged and used for exchange.

3. Device certificate: Public key certificates for the main and slave devices under the brand, which is non-volatile storaged and used for exchange.

4. ML-KEM_n: ML-KEM Parameters, which is non-volatile storaged and local use.

5. ML-KEM_q: ML-KEM Parameters, which is non-volatile storaged and local use.

6. ML-KEM_k: ML-KEM Parameters, which is non-volatile storaged and local use.

7. ML-KEM_1: ML-KEM Parameters, which is non-volatile storaged and local use.

8. ML-KEM_2: ML-KEM Parameters, which is non-volatile storaged and local use.

9. ML-KEM_: ML-KEM Parameters, which is non-volatile storaged and local use.

10. ML-KEM_v: ML-KEM Parameters, which is non-volatile storaged and local use.

11. MK_EK: Device’ s ML-KEM public key, encapsulated key, which is non-volatile storaged and used for exchange.

12. MK_DK: Device’ s ML-KEM private key, unpacking key, which is non-volatile storaged and local use.

13. ML-DSA_q: ML-KEM Parameters, which is non-volatile storaged and local use.

14. ML-DSA_: ML-KEM Parameters, which is non-volatile storaged and local use.

15. ML-DSA_: ML-KEM Parameters, which is non-volatile storaged and local use.

16. ML-DSA_: ML-KEM Parameters, which is non-volatile storaged and local use.

17. ML-DSA_: ML-KEM Parameters, which is non-volatile storaged and local use.

18. ML-DSA_1: ML-KEM Parameters, which is non-volatile storaged and local use.

19. ML-DSA_2: ML-KEM Parameters, which is non-volatile storaged and local use.

20. ML-DSA_(,): ML-KEM Parameters, which is non-volatile storaged and local use.

21. ML-DSA_: ML-KEM Parameters, which is non-volatile storaged and local use.

22. ML-DSA_: ML-KEM Parameters, which is non-volatile storaged and local use.

23. ML-DSA_: ML-KEM Parameters, which is non-volatile storaged and local use.

24. MK_PUBK: Device’ s ML-DSA Public Key, which is non-volatile storaged and used for exchange.

25. MK_PRIK: Device’ s ML-DSA Private Key, which is non-volatile storaged and local use.

26. KEM_C: Content key encapsulation value, which is volatile storaged and used for exchange.

27. KEM_BC: Broadcast content key encapsulation value, which is volatile storaged and used for exchange.

The keys stored in the certificate hierarchy mainly include ECC and post quantum algorithm public cryptographic protocol parameters, private keys of the master client and slave server, and public key certificate chains. The public key certificate chain includes root certificates, vendor certificates, and device certificates. The device certificate includes the device’s ID number, ECC public key, post quantum algorithm public key, and other attribute information of the certificate. The key data at this level is mainly used to execute authentication protocols. After device initialization, the certificate must not be changed or replaced. It is recommended to use mature OTP memory based on eFuse or Anti-Use technology, OTP non-volatile memory, and data that cannot be reversibly modified after writing. The definition of protection methods for these data is not within the scope of this draft document.

For master-slave devices, MK-DK and MK-PRIK are the main private keys for both parties. MK-DK is mainly used for key encapsulation, while MK-PRIK is the main private key for the signing process, which must be ensured not to be modified or intercepted by third parties. It is recommended to use a mature TEE environment. The definition of protection methods for MK-DK and MK-PRIK keys is not within the scope of this draft document.

5.2.4.2. Authentication and Key Agreement Mechanism

The authentication and key negotiation based on post quantum hybrid signature PKI public key certificate includes certificate verification, generation of CK and BCK keys. Firstly, in the first stage, the authentication process between the master client and the slave server begins by exchanging their respective certificate chains rooted in ROT. The master client must verify the certificate chain of the slave server, and similarly, the slave server must also verify the certificate chain of the master client. During the verification process, the slave server will extract the CLIENT ID (64 bit data) from the master client’s public key certificate, and similarly, the master client will also extract the SERVER ID (64 bit data) from the slave server’s public key certificate. The verification priority for certificate chains with mixed signatures is as follows. If all certificates on the certificate chain have ECC parameters that meet legal requirements, they should be processed directly according to the protocol in Section "Modbus Serial Link Security Protocol Based on ECC Public Key Certificate". If ECC parameters are non-compliant, such as key length non-compliance or mandatory use of post quantum algorithms, they should be handled according to post quantum mechanisms. If post quantum related parameters are also non-compliant, the current certificate chain of the device should be considered non-compliant.

In the first stage, the slave server and master client based on post quantum algorithms must perform a key encapsulation exchange mechanism using device certificates to obtain a long-term secret master key KEMSK and a long-term authentication key (which can reduce the first stage of public key authentication operations when the master and slave devices are powered on for re authentication, as described in the "Authentication Context and Re authentication" section below). Subsequently, both parties should generate temporary content encryption keys based on KEMSK. Both parties should store the master key KEMSK and authentication key in NVM and keep them confidential for subsequent Modbus protocol data communication encryption key derivation.

In the second stage, the slave server will send a request to the master client to confirm the authentication key. After receiving the confirmation message, the slave server must compare the received key value with the stored key value. If the two are consistent, it can prove that the master client is legitimate.

The authentication and key negotiation steps based on post quantum hybrid signature PKI public key certificate are shown in Figure 51, and the message semantics are explained as follows:

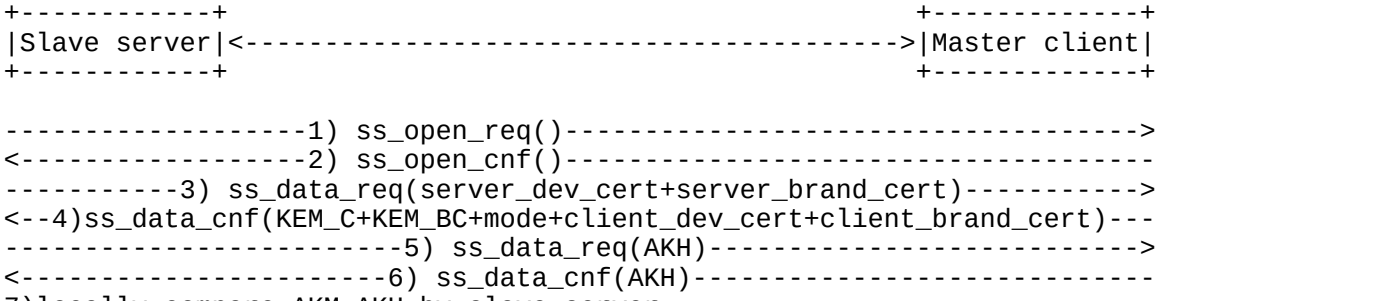


Figure 51: Authentication and Key Agreement Message Exchange Based on Post Quantum Certif
icate

1. The slave server sends ss_open_req APDU to the master client.

2. The master client responds with ss_open_cnf APDU.

3. Send ss_data_req APDU from the slave server to the master client. The message contains: 1) Device certificate (Server_dev_Cert) of slave server; 2) Brand certificate (Server_Brand_Cert) of slave server; 3) ID of the requested data type.

4. The master client responds with ss_data_cnf APDU. The message contains: 1) Key encapsulated message ciphertext (KEM-C) of the master client; 2) Key encapsulated message ciphertext (KEM-BC) of the master client; 3) Encryption and decryption mode 4) Device certificate (Client_Dev_Cert) of master client; 5) Brand certificate (Client_Brand_Cert) of master client. Failure to respond to this message may result in a system error, possibly due to the master client being unable to verify data from the slave server.

5. The slave server sends ss_data_req APDU to the master client. The message contains: 1) The data type ID of the requested AKH.

6. The master client responds with ss_data_cnf APDU. The message contains an AKH, Either it is valid or it is all zero, indicating illegality. Failure to respond to this message will result in a system error.

7. The slave server compares the received AKH with the locally calculated AKM. If there is inconsistency, it will result in a system error.

The APDU format of the protocol based on post quantum certificate authentication and key agreement protocol, which includes specific data types, is shown as below:

When sending public key certificate chain from the slave server to the master client, ss_data_req APDU is sent with following Parameters in Figure 52.

content		
send _datatype_nbr=2		
i	datatype_id	datatype_len
0	11(Server_Dev_Cert)	1280 bits
1	4(Server_Brand_Cert)	1280 bits
request_datatype_nbr=5		
i	datatype_id	
0	26 (KEM_C)	
1	27 (KEM_BC)	
2	24 (mode)	
3	10 (Client_Dev_Cert)	
4	3 (Client_Brand_Cert)	

Figure 52: ss_data_req APDU content

When the master client sends KEM-C, KEM-BC,encryption mode and two public key certificates, ss_data_cnf APDU is sent with following Parameters in Figure 53.

content		
send _datatype_nbr=5		
i	datatype_id	datatype_len
0	26 (KEM_C)	8704 bits
1	27 (KEM_BC)	8704 bits
2	24 (mode)	8 bits
3	10 (Client_Dev_Cert)	1280 bits
4	3 (Client_Brand_Cert)	1280 bits

Figure 53: ss_data_cnf APDU content

When requesting AKH from the slave server to the master client, ss_data_req APDU is sent with following Parameters in Figure 54.

content		
request_datatype_nbr=1		
i	datatype_id	
0	17(AKH)	

Figure 54: ss_data_req APDU content

When the master client sends AKH, ss_data_cnf APDU is sent with following Parameters in Figure 55.

content		
send _datatype_nbr=1		
i	datatype_id	datatype_len
0	17(AKH)	256 bits

Figure 55: ss_data_cnf APDU content

Note: During the certificate authentication phase, APDU messages will encapsulate the Modbus serial link data unit field with a success number of 0. For APDUs larger than 252 bytes (the maximum data field length of Modbus RTU frames), such as ss_data-req APDUs, which exchange certificates with approximately 422 bytes, they can be divided into two Modbus serial link message frames for transmission. Since the transmission operation is strictly serial and has a sequence, the upper layer application can concatenate two or more segmented APDUs based on the tag (ss_data_cnf_tag) and length_field () fields of the protocol.

The calculations involved in the authentication and key negotiation process based on post quantum certificates are shown as below:

1. The slave server sends its public key certificate chain to the master client.

2. The master client verifies the validity of the two received certificates from the slave servers.

3. The master client uses appropriate PRNG to generate two 32 byte random numbers, and calculates and obtains a master key KEMSK and a broadcast master key KEMSK_B according to the ML-KEM.Encaps algorithm, as well as their corresponding encapsulated key ciphertexts KEM-C and KEM-BC.

4. The master client sends the encapsulated key ciphertexts KEM-C, KEM-BC, as well as the master client device certificate and the brand certificate of the master client device manufacturer to the slave server.

5. The slave server verifies the validity of the received two certificates.

6. The slave server verifies the parameters, use KEM-C and ML-KEM.Decaps algorithms to calculate the 32 byte master key KEMSK and broadcast master key KEMSK_B, respectively, and calculate and store the authentication key (AKM).

7. The master client calculates and stores the authentication key (AKH).

8. The slave server start to enter the second stage of the authentication process: request the current authentication key AKH from the master client through the response APDU.

9. The master client uses the corresponding APDU to send AKH to the slave server.

10. The slave server compares the received AKH with its own calculated AKM. If they are different, it will result in a system error.

Step 1: Calculation of authentication keys (AKH and AKM), which can be used in subsequent authentication processes. The authentication key is generated when the master client and slave server are first bound and stored in NVM, which can be used for repeated authentication in the future. The calculation process is as follows: AKM = AKH = SM3(SERVER_ID||CLIENT_ID||KEMSK)

Step 2: Export CK and CIV. CK = MSB128(SM3(KEMSK||SERVER_ID)), CIV = LSB128(SM3(KEMSK||SERVER_ID))

Step 3: Export BCK and CIV, and use the broadcast master key KEMSK_B for broadcast communication between the master client and all slave servers. BCK = MSB128(SM3(KEMSK_B||CLIENT_ID)), BCIV = LSB128(SM3(KEMSK_B||CLIENT_ID))

Authentication context and re-authentication: Authentication context is a secure data object stored in NVM, and its storage format is not strictly defined in this specification. However, in the implementation of actual products, it should be given sufficient security to ensure that it is not changed by attackers. The authentication context is used to store the results of public key authentication between both parties of the device, and is used to perform the re authentication process. The information that should be included in the authentication context of the slave server and master client is shown in Figure 56.

Slave server	Master client
CLIENT_ID	SERVER_ID
KEMSK	KEMSK
AKM	AKM
Encryption mode	Encryption mode

Figure 56: Information in Authentication Context

After the master client and slave server are first bound, the device should associate the DHSK and authentication key negotiated during the public key authentication process with an authentication context. The master client should support at least 247 authentication contexts, and the slave server should support at least 1 authentication context.

After establishing a session, the master client and slave server can first perform an authentication key verification step to check if there is an existing binding relationship between the two devices. If there is, there is no need to perform a public key authentication protocol. If the slave server has a valid authentication context, it should directly request the master client to send an AKH and then check if the received AKH matches the AKM in the local authentication context. If there is inconsistency, the slave server shall attempt up to 246 more times (as the master client may have 247 authentication contexts). When there are no other available authentication contexts for the master client, the master client should send a zero value as a response to the AKH request from the slave server, and the slave server should start executing the public key authentication protocol. If the master client has the authentication context of the slave, it should first send the AKH in the context of the slave. If the AKH is inconsistent with the AKM of the slave server, the slave server should attempt to request AKH again, and the master client should send other AKHs in other authentication contexts. So, re-powering on the slave server may not necessarily execute the public key authentication protocol to reduce authentication time. But when the slave server accesses an unbound master client, or when the master client accesses an unbound slave server, the identity authentication protocol related to the public key certificate is required to be executed.

5.2.4.3. Content Encryption and Decryption Mechanism

The content encryption and decryption mechanism used in this section is the same as that in previous section.

6. Appendix A

Parameter datatype id table exchanged in APDU. Table A.1 summarizes the parameters and data type ID number used in this draft document.

Table A.1: System parameter numbers in secure communication protocol calculation

Keywords or variables	No, of bits	datatype id
CLIENT_ID	64	1
SERVER_ID	64	2
Client_Brand_Cert	variable	3
Server_Brand_Cert	variable	4
Reserved	--	5

Reserved	--	6
Kp	256	7
DHPH	512	8
DHPM	512	9
Client_dev_Cert	variable	10
Server_dev_Cert	variable	11
RM(Signature_A)	256	12
RH(Signature_B)	256	13
auth_nonce	256	14
Ns_H	64	15
Ns_M	64	16
AKH	256	17
AKM	256	18
Reserved	-	19
status_field	8	20
Reserved	-	21
R_H/R_M	512	22
r_B	256	23
mode	8	24
S_M/S_H	256	25
KEM_C	8704	26
KEM_BC	8704	27

7. Appendix B

Pseudo-random number generator. The random numbers generated by the pseudo-random number generator PRNG in this draft document are shown in Table B.1.

Table B.1: Parameters for Using Pseudo Random Number Generator

random number	No, of bits	description
DHX	256	DH exponent "x"
DHY	256	DH exponent "y"
Kp	64	Used to establish SAC
Ns_H	64	Used to establish SAC
Ns_M	64	Used to establish SAC
r_B	256	Used to generate BCK

This draft document requires the use of FIPS-140-2 and a pseudo-random number generator defined by [SCTE 41:2004], section 4.6, RGB required by NIST.FIPS.203, NIST.FIPS.204 and An AES based pseudo-random number generator by ANSI X 9.31 1316H [ANSI X 9.31:1998].

8. Appendix C

Trust Model and Certificate Format

1) Trust Model:

The Modbus serial link communication security protocol based on traditional ECC PKI public key certificate adopts a tree shaped PKI structure, as shown in Figure C.1. The system has only one trust root (ROT), which issues public key certificates to industrial equipment manufacturers of different brands, and can also issue public key certificates to different business operators (factories). In addition, ROT also issues equipment certificates for different brands of industrial equipment manufacturers for their respective equipment brands. In actual operation, these brand certificates and equipment certificates can be issued by the original factory in the product at the time of leaving the factory, or they can be deployed and operated in the product by third-party agents or the most network user factory after leaving the factory.

The trust model structure based on post quantum hybrid signature PKI public key certificate is the same as the tree structure of traditional ECC PKI method, but the difference is that ROT will have two independent certificates generated by ECC algorithm and post quantum algorithm respectively.

The brand certificate contains the signature public keys required for ECC algorithms such as SM2 and post quantum signature algorithms such as ML-DSA, which consist of two public keys that can be concatenated and stored in the subjectPublicKeyInfo field, AlgorithmIdentifier is defined as SM2withSM3+ML-DSA, or they can be stored separately in the subjectPublicKeyInfo field and the extension field of the main public key information. The extension field includes Key Usage: Digital Signature, id-oqs-public-key: ML-DSA Public Key, id-oqs-algorithm: ML-DSA. In addition, the brand certificate also includes corresponding signatures generated from two ROT certificates and combined in a single signature format in the Signature field of the certificate (i.e. containing two signatures). The specific storage form is not mandatory in this draft document.

The device certificate contains the public key required for ECC algorithms such as SM2 and the public key required for post quantum key encapsulation algorithms such as ML-KEM, as well as signatures generated by the corresponding brand certificate through ECC algorithm and ML-DSA algorithm private key respectively, and combined in a single combination signature in the Signature field of the certificate (i.e. containing two signatures). The specific storage form is not mandatory in this draft document.

Based on post quantum hybrid signature PKI public key certificate, referring to NIST recommendations and considering protocol application scenarios, this draft document recommends KEM algorithm to support ML-KEM-768, while DSA signature algorithm is recommended to support ML-DSA-44.

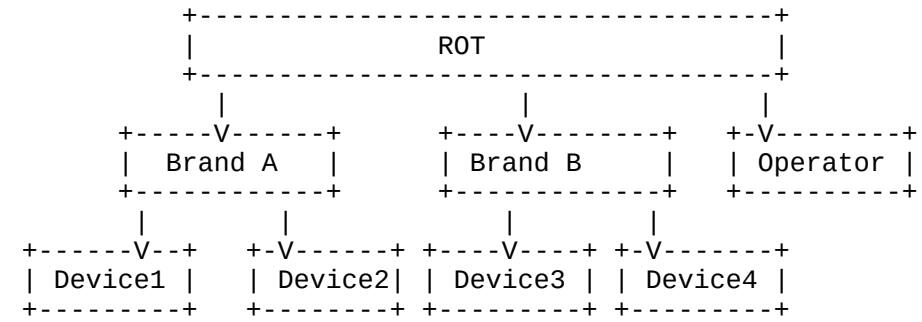


Figure C.1: Trust Model

1) Certificate format and content:

The Modbus serial link communication security protocol based on ECC public key certificates has three types of public key certificates: ROT root certificate, manufacturer brand certificate, and device certificate. Each device stores the root certificate of ROT, device certificate, and the corresponding manufacturer's brand certificate in its NVM. The root certificate is a self-signed certificate used to verify the manufacturer's brand and device certificate. The manufacturer's brand certificate is issued by ROT and is used to verify the equipment certificate. These three types of certificates have a unified field format, following the X.509 format. The basic and extended fields they contain are shown in Table C.1. They are distinguished by the "Certificate Type" field in the certificate.

Table C.1: Certificate Fields and Structure

syntax	No. of bits	Mnemonic
Modbus_certificate(){		
modbussec_ID	8	bslbf
certificate_type	8	bslbf
certificate_version	8	bslbf
encryption_capability	8	bslbf
holder_ID	64	bslbf
holder_public_key_x	256	uimsbf
holder_public_key_y	256	uimsbf
issuer_ID	64	bslbf
signed_date	32	bslbf
reserved	64	bslbf
signature_c	256	uimsbf
signature_d	256	uimsbf
}		

Modbussec-ID: This field represents the security system to which the certificate belongs, and this section specifies its value as 0xC2.

Certificate type: This field represents the type of certificate. See Table C.2.

Table C.2: Certificate Types

Certificate_type	The type of certificate represented
0x00	Root certificate
0x01	Operator certificate
0x02	Brand certificate
0x03	Device certificate
Others	Reserved

Certificate_version: This field represents the version of the certificate, and this section specifies that the version number for all types of certificates is 0x01.

Encryption_capability: This field represents the encryption modes supported by the device, and AES algorithm is used by default, as shown in Table C.3.

Table C.3: Encryption and Decryption Capability

encryption_capability	description
0x00	Reserved
0x01	For device supporting aes_gcm
0x02	For device supporting sm4_gcm
0x04	For device supporting zuc
0x08	For device supporting chapoly
Others	Reserved

Holder_ID: This field represents the ID of the certificate holder, which is SERVHER-ID or CLIENT-ID.

Holder_public_key_x: This field represents the horizontal axis value of the certificate holder’s public key.

Holder_public_key_y: This field represents the y-axis value of the certificate holder’s public key.

Issue_ID: This field represents the ID of the certificate issuer, which is the holder ID in the certificate issued by the CA that issued the certificate.

Signed_time: This field represents the date of issuance of the certificate. This time is composed of the lower 16 bits of MJD time and four 4-bit BCD digits. For example, on October 13, 1993, 12:45 was encoded as "0xC0791245".

Reserved: Set all fields to zero for future expansion.

Signature_c: This field represents the c value of the certificate issuer’s digital signature on the certificate data.

Signature-d: This field represents the d value of the digital signature of the certificate issuer on the certificate data.

Note: The certificate signature scheme adopts ECSSA scheme in 10.2 of IEEE 1363-2000 standard, the signature algorithm adopts ECSP-DSA algorithm in 7.2.7 of IEEE 1363-2000 standard, the message encoding method adopts EMSA1 method in 12.1.1 of IEEE 1363-2000 standard, and the hash function in the encoding method adopts SHA-256. Alternatively, the SM2 and SM3 algorithms in the ISO/IEC 14888-3:2018 standard can be used.

Note: The verification algorithm corresponding to the above signature algorithm is the ECVP-DSA algorithm or SM2 and SM3 algorithms in 7.2.8 of the IEEE 1363-2000 standard.

The PKI public key certificate based on post quantum hybrid signature follows the X.509 format, which includes basic and extended fields as shown in Table C.4.

Table C.4: PKI Public Key Certificate Fields and Structure Based on Post Quantum Hybrid Signature

syntax	No. of bits	Mnemonic
Modbus_certificate(){		
modbussec_ID	8	bslbf
certificate_type	8	bslbf
certificate_version	8	bslbf
encryption_capability	8	bslbf
holder_ID	64	bslbf
holder_public_key_x	256	uimsbf
holder_public_key_y	256	uimsbf
ml_dsa_public_key	1312*8	uimsbf
(For brand certificate)		
ml_kem_public_key	1312*8	uimsbf
(For device certificate)		
issuer_ID	64	bslbf
signed_date	32	bslbf
reserved	64	bslbf
signature_c	256	uimsbf
signature_d	256	uimsbf
signature_s	2420*8	uimsbf
}		

ml_desa_public_key: This field represents the ML-DSA algorithm public key of the certificate holder, which is only applicable to brand certificates.

ml_kem_public_key: This field represents the ML-KEM algorithm public key of the certificate holder, which is only applicable to device certificates.

signature_s: This field represents the ML-DSA algorithm signature in the mixed signature of the certificate.

The meaning of other fields is the same as mentioned above.

3) Certificate holder ID

In order to support different revocation granularity requirements in the future, when the certificate type is "device certificate", further definition of the holder_ID domain is required, as shown in Figure C.2.

1. Define the top 16 bits in the "holder-ID" field (64 bits) as the " device brand identifier";

2. Define the lower 32 bits of the "holder-ID" field (64 bits) as the "device serial number";

3. Define the middle 16 bits of the "holder-ID" field (64 bits) as the "device model identifier".

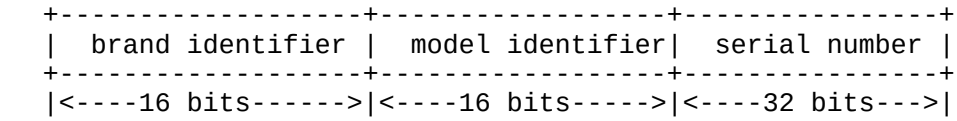


Figure C.2: Structure of Certificate Holder ID

In addition, this section requires that when the certificate type is "device certificate", the values of “device brand identifier" and "device model identifier" cannot be zero; The " device brand identifier" and "device model identifier" in the IDs of the other types of certificates are both set to zero values.

4) Elliptic curve parameters

The Modbus serial link communication security protocol based on public key certificates in this document uses the elliptic curve defined in the prime field according to the SM2 standard, where:

EC_p=0x8542D69E 4C044F18 E8B92435 BF6FF7DE 45728391 5C45517D 722EDB8B 08F1DFC3 EC_a=0x787968B4 FA32C3FD 2417842E 73BBFEFF 2F3C848B 6831D7E0 EC65228B 3937E498 EC_b=0x63E4C6D3 B23B0C84 9CF84241 484BFE48 F61D59A5 B16BA06E 6E12D1DA 27C5249A

The order of the above curve is:

EC_N=0x8542D69E 4C044F18 E8B92435 BF6FF7DD 29772063 0485628D 5AE74EE7 C32E79B7

The coordinates of the base point EC_G=(Gx, Gy) on the curve:

Gx=0x421DEBD6 1B62EAB6 746434EB C3CC315E 32220B3B ADD50BDC 4C4E6C14 7FEDD43D Gy=0x0680512B CBB42C07 D47349D2 153B70C4 E5D7FDFC BFA36EA1 A85841B9 E46E09A2

9. IANA Considerations

This memo includes no request to IANA.

10. Security Considerations

This specification defines the reference native security protocol specification for the case with pure serial link communication, which (e.g., RS485-based Modbus) remains an unresolved challenge. Serial Modbus transmits data in plaintext, leaving it susceptible to interception, modification, and hardware-based side-channel attacks. There are currently no formal standards addressing security for Modbus over RS485, which is still widely used due to its simplicity and long-distance capabilities. Currently, for any EIA/TIA-485 multi-point system, whether it is a 2-wire or 4-wire configuration, the maximum length for cables with a maximum baud rate of 9600bit/s and AWG26 (or thicker) specifications can reach over 1000m. For RS485 Modbus, a sufficiently wide cable diameter should allow for a maximum length of over 1000m, and for RS485 Modbus using Category 5 cables, the maximum length can reach 600m. This lack of encryption and authentication mechanisms poses risks, particularly in scenarios involving relays or bridged networks. While Modbus TCP has seen notable advancements in security through TLS-based solutions, serial Modbus communication requires more attention. Introducing lightweight encryption and authentication mechanisms for serial links could provide a practical way to enhance security and protect legacy systems without significant infrastructure changes. Therefore, it is very necessary and valuable to improve and enhance the communication security of Modbus protocol under serial link mode, for reference by relevant institutions and organizations in various industries, in order to ensure the practical application security of various industrial control systems. With the introduction of the Modbus

serial link security standard, the introduction of encryption and authentication mechanisms in the serial link communication channel of the Modbus protocol significantly improves its security, providing a relatively simple and direct upgrade path for existing devices that use Modbus extensively.

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Authors' Addresses

Penghui Liu (editor)
Pengcheng Laboratory
No.2 Xingke 1 Street
Shenzhen
518055
China
Email: liuph@pcl.ac.cn

Rongwei Yang (editor)
Pengcheng Laboratory
No.2 Xingke 1 Street
Shenzhen
518055
China

Email: yangrw@pcl.ac.cn

Meiling Chen (editor)
China Mobile
No.32 Xuanwumen West Street
Beijing
100000
China
Email: chenmeiling@chinamobile.com

Yu Fu (editor)
China Telecom
No. 3 Penglaiyuan South Street
Beijing
100000
China
Email: fuy44@chinatelecom.cn

Weizhe Zhang (editor)
Pengcheng Laboratory
No.2 Xingke 1 Street
Shenzhen
518055
China
Email: zhangwzh@pcl.ac.cn