Codimension-Two Free Boundary Problems

Keith Gillow
St Catherine's College
University of Oxford

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Contents

List of Figures

Chapter 1

System Description

1.1 System Model

1.1.1 Overview

This protocol is typically used under the scenario that there is no reliable or stable networks existed between communication entities (called Alice and Bob). Entities under such conditions can be abstracted as off-line entities in the sense that their network is restricted and can not reach the others' networks. This system allows those off-line entities to communicate by using a Courier to deliver the message. Assuming Alice wants to send a message to Bob, the Courier firstly gets the message from Alice and stores it, then physically transport to Bob and send the message to Bob.

The goal of this protocol is to ensure the message from Alice to Bob is secure in the sense that no one can reveal its content but Bob. To achieve that, the Courier should never be trusted, which means the real content of the message should not be accessed by Courier and both Alice and Bob are able to deny the communication with Courier at any time. Furthermore, to prevent sensitive information from being leaked by malicious message recipient (Bob), message creator (Alice) should be able to deny the message content as well.

1.1.2 Initial Set-ups

According to the description above, totally 3 different types of entities are defined in the protocol - Alice, Bob and Courier. Following specification lists the notations and jobs of all 3 entities together with the information they should hold before running the protocol:

- Alice $\mathcal{A}$ denotes a set of devices who create the message and waits it to be delivered. It possesses an unique $\mathcal{ID} \in \{0,1\}^*$, a secret key sk_A as part of its asymmetric key pair, and the message $\mathcal{M}$ to be sent.
  $\mathcal{A}$'s ID and public key should be known by at least one Courier so that it will be connected by Courier.

- Bob $\mathcal{B}$ denotes a set of devices who wait incoming messages delivered by Courier. It possesses an unique $\mathcal{ID} \in \{0,1\}^*$, and a secret key sk_B as part of its asymmetric key pair.
  Similarly, its ID and public key should also be known by at least one Courier.

- Courier $\mathcal{C}$ denotes a set of devices who carry the message of Alice, physically transport from Alice to Bob, and deliver the message to Bob. Initially it only possesses an unique $\mathcal{ID} \in \{0,1\}^*$ and at least a contact $\mathcal{ID} \in \{0,1\}^*$ and its corresponding public key, specifies the entity it is going to contact.
  However, a single Courier will play two different roles in the protocol run - one receives message from Alice, one delivers message to Bob. They are denoted as $\mathcal{CR}$ (Courier Receiver) and $\mathcal{CS}$ (Courier Sender) in the protocol specification. In addition to $\mathcal{CR}$, $\mathcal{CS}$ possesses some more information: the $\mathcal{ID}$ of the message creator and the encrypted message received from $\mathcal{A}$.

Public Key Distribution The distribution of asymmetric key pairs used for authentication is out of the scope of this protocol, thus $\mathcal{A}$ and $\mathcal{B}$ are assumed to hold their asymmetric key pairs before running the protocol. Furthermore, all entities in the system are assumed to know each other's public key (does not matter it is distributed with manufacture, authenticated by CA, or by key exchange), before running the protocol.

Devices v.s. Entities A device x denotes a physical object that runs the protocol. Differently, an entity denotes a particular role in the running of the protocol. It should be noted that any device can run multiple instances of this protocol with other devices simultaneously, thus a single device can be any three entities at the same time. The role it plays in different communications is defined by what information x holds and what sub-protocol it runs (will be described in Communication Model). However, an entity in the protocol can be associated with only one device.

1.1.3 Communication Model

Ultimately, every single run of this protocol achieves an abstract M-to-1 communication - a certain number of devices $a_0, a_1, ...a_M \in \mathcal{A}$ send message to a single device $b_0, b_1, ..., b_M \in \mathcal{B}$ independently, using a device $c \in \mathcal{C}$ as media. As physical transportation is extremely slow and costly compare to network communication, the total number of physical transportation should be reduced to minimum. The optimized solution appeared to be separating the protocol into two main phases - Message Acquisition phase and Message Delivery phase. Assume off-line devices $a_1, a_2, ...a_M \in \mathcal{A}$ need to send message to the off-line device $b \in \mathcal{B}$. In Message Acquisition phase, a Courier will physically transport to every $a \in \mathcal{A}$, connect to it and get the message that is for the b. After the Courier collects all needed messages, it enters Message Delivery phase, where the Courier transports to b and transmit all acquired messages to it.

According to explanation above, the whole task can be divided into M + 1 individual communications. Every such individual communication happens between a Courier $c \in \mathcal{C}$ and one of $\mathcal{A} \cup \mathcal{B}$ after the Courier connects to the target. All these communications use one of typical network communication methods (e.g. cable, Wifi, Bluetooth, etc.) and apply its corresponding communication protocols (e.g. TCP/IP, UDP, Bluetooth protocol, etc.). The following figure shows how the communication is organized.

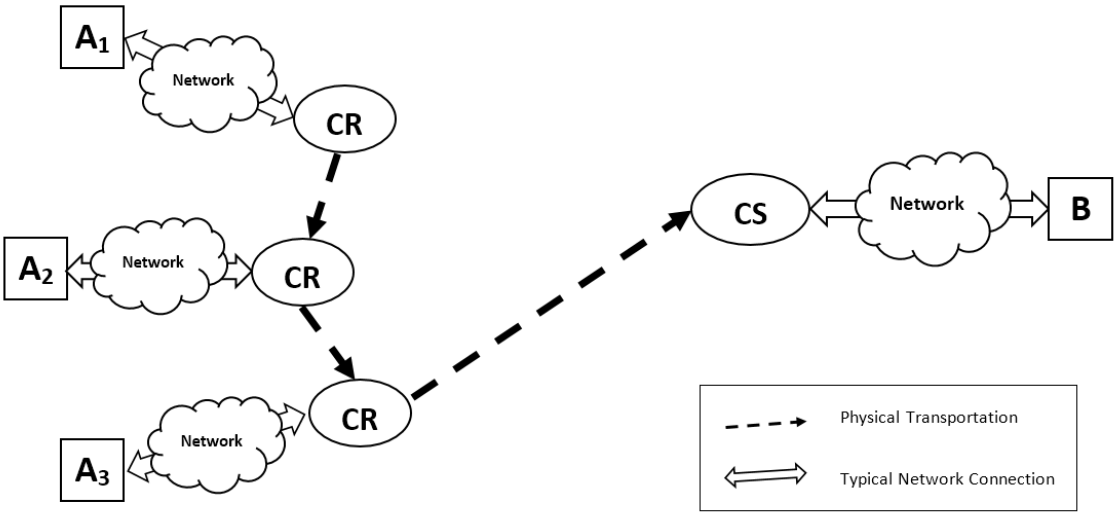


Figure 1.1: Communication Model

The figure "Communication Model" illustrates the procedure of a 3-to-1 communication. The Courier first connects to A_1, be the role of $\mathcal{CR}$, and gets A_1's message

for B through the connection, then disconnects and transports to A_2. It should do the same thing to A_2 and then transport to A_3. After it collects all data from A_1, A_2 and A_3, it transports to B and be the role of $\mathcal{CS}$ to send all collected messages to B. The networks between Courier and As or B can be any kind of connection and do not to be the same, as long as both entities accept.

To define different kinds of communication, this protocol consists of 2 sub-protocols - a) Submit protocol: how message is submitted from $\mathcal{A}$ to $\mathcal{C}$; b) Transmit protocol: after $\mathcal{C}$ gets connected with $\mathcal{B}$, how message is transmitted to $\mathcal{B}$. These two sub-protocols ensure the secure transmission of message from $\mathcal{A}$ to $\mathcal{B}$ and they will be analysed in the later part.

1.1.4 Honest Entity Behaviour

Generally, all 3 entities in this protocol act as devices who possess their own initial information (described above), take $\mathcal{M}$ as input, and output $\mathcal{M}'$. All honest entities in this protocol should follow the following procedure:

1. If entity is $\mathcal{C}$, initiate the protocol by sending $\mathcal{M}_0{}'$, otherwise ignore this step.
2. Wait for $\mathcal{M}_1$
3. Receive $\mathcal{M}_1$, decrypt all its ciphertexts and reveal their contents if applicable.
4. Check validity of the contents of $\mathcal{M}_1$ (e.g. check message format, check sender ID, receiver ID, digital signature or MAC, if applicable). If any check violates, immediately report "Protocol Error" and abort the session.
5. Process the message content (e.g. print the result, stores the contents in local storage).
6. Prepare and send message $\mathcal{M}_1{}'$. If no message to send, abort the session silently.
7. Back to step 2.

However, three entities have different behaviour patterns, they will be specified here, respectively:

Alice $\mathcal{A}$

- An entity $a \in \mathcal{A}$ create the message to send, and prepare its meta data. Then it continuously listening to its network, waiting for incoming Couriers.
- Alice will submit its message to any Courier who request for it. When submitting, the message recipient must be explicitly specified.
- Alice is allowed to submit any message arbitrary times, to single or multiple Couriers. Alice itself should not care who carries the message, nor how many Couriers carry the message.
- During an uncompleted session, if no response from Courier for a long time, Alice should be able to detect the timeout, cancel the effects of previous actions in this session and abort the session voluntarily.
- If the message is not successfully sent, Alice should wait for next Couriers to send this message.

Bob $\mathcal{B}$

- An entity $b \in \mathcal{B}$ must be continuously listening to its network, waiting for incoming messages.
- Bob will download all messages from any Courier who transmits. If any message from $\mathcal{A}$ is invalid, Bob simply discards it.
- Bob will discard all duplicated messages. Duplicated message are defined as messages whose Meta Signature are exactly the same. Because message Meta contains its creator ID and timestamp, same Meta reflects those messages are created by the same entity at the exact same time.
- During an uncompleted session, if no response from Courier for a long time, Bob should be able to detect the timeout, cancel the effects of previous actions in this session and abort the session voluntarily.

Courier $\mathcal{C}$

- As Courier's physical transportation is a very complicated task, it is out of the scope of this protocol. It is assumed that Courier is carried by an intelligent agent (such like human) who always knows where the Courier should transport to.
- Courier should transport to every $a \in \mathcal{A}$ one by one and get their messages if there are any. Courier should be capable of storing those data for a long time.
- After collect messages from all a in the list, Courier should transport to every b that is the recipient of the Courier and deliver all messages to them. If the receipt from b violates the messages Courier just sent, Courier should resend the messages by restart the session again.
- Once a full protocol run has been completed, all relative data stored in Courier is expired and should not affect future run of protocol.

1.2 Adversary Model

The adversary model in this protocol is mostly derived from Dolev-Yao model which implies "adversary carries the message" [**?**]. Moreover, the adversary can also do something special in this protocol system. Specifically, adversary $\mathcal{Z}$ has following capabilities:

- It supervises the whole network system, which means it knows when, where and how any two entities are communicating, and it knows which entity possesses what information.
- It can access/rewrite any message passing through the network.
- It is a legitimate user of the network and it can be any of 3 entities in this protocol.
- It can access to all the Courier's data at any stage of the protocol.
- Any $a \in \mathcal{A}$ or $b \in \mathcal{B}$ will always have the opportunity to be connected by any $c \in \mathcal{C}$, which means an adversary will always have opportunity to be contacted by any honest entities.

It should be noted that this protocol, same as all other network protocols, is vulnerable to DoS attacks. $\mathcal{Z}$ can always prevent a message from being sent, thus it will not be covered in the security analysis.

Chapter 2

Protocol Specification

A successful run of CDSProtocol consists of 3 stages - (1) message creators submit their messages to a single courier. (2) courier physically transports to the message receiver. (3) courier transmits the messages to the message receiver. As controlling couriers and planning couriers' routes are out of the scope of this protocol, it is assumed that in this protocol, couriers eventually are able to approach the target. Therefore stage (2) will not be discussed here.

The protocol specification will focus on the other two stages - (1) and (3), we call them Message Acquisition phase and Message Delivery phase. To ensure secure communication in both two phases, two sub-protocols - Submit Protocol and Transmit Protocol, are defined for those two phases respectively. The Submit Protocol runs between Alice and Courier, while the Transmit Protocol runs between Bob and Courier. As those two sub-protocols can be run independently, they will be explained separately.

2.1 Notations

The detail entity operations and message sequences of two sub-protocols will be displayed in message sequencing charts separately. Before showing those charts the notations are introduced first.

Encryption Functions $\mathcal{E}_k$: This notation denotes an abstraction of all encryption functions, including both symmetric and asymmetric encryptions. The subscript k denotes the key used for the encryption processes, and it is used for differentiating symmetric and asymmetric encryption, such like if the key is specified as an asymmetric key, it indicates the function is an asymmetric encryption, while symmetric key indicates symmetric encryption.

Decryption Functions $\mathcal{D}_k$: Similar to encryption functions, this notation denotes symmetric and asymmetric decryption functions, and subscript k denotes the key used for decryption.

Message Authentication Code Function $\mathcal{MAC}_k$: It denotes an abstract MAC function, and the subscript k indicates the key used for the function.

Digital Signature Function $\mathcal{SIGN}_E$: It denotes an abstract digital signature function, and the subscript E indicates the entity who creates this signature using a secret key sk_A. And it can only be verified under the corresponding public key pk_B.

Concatenation ||: It denotes the operation that concatenates two pieces of data together. For example "A||B" simply means appending B to A.

Accumulation $^+$: It represents many pieces of data which have same format accumulated together. For example "ID^+" equals a sequence of IDs concatenated together, which can be "ID_0" or "$\text{ID}_0||\text{ID}_1$" or "$\text{ID}_0||\text{ID}_1||...$" where it contains at least one ID and the content of IDs can be different.

2.2 Submit Protocol

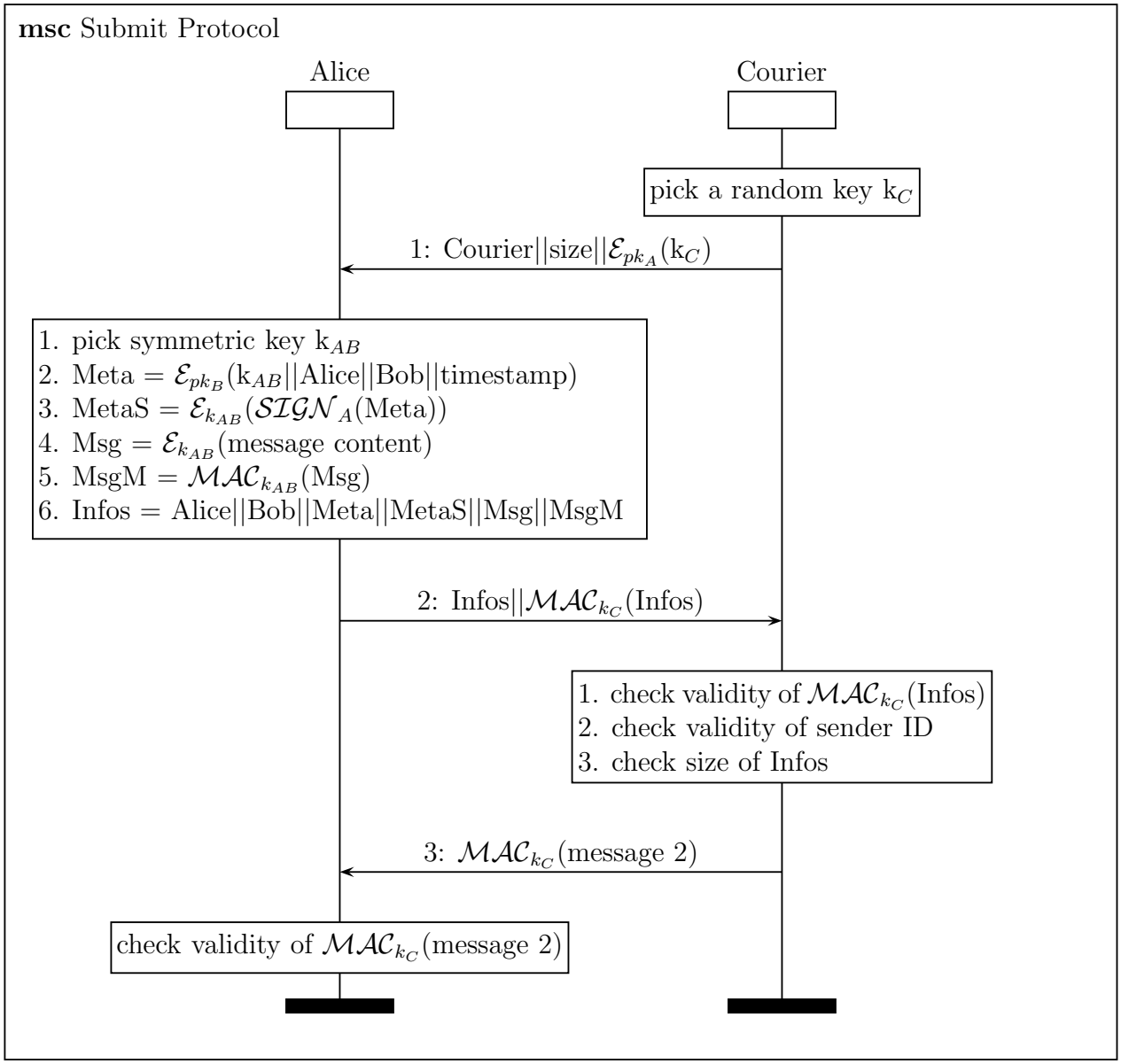
2.2.1 Preconditions

- Alice holds a unique pair of asymmetric key (pk_A, sk_A)
- Courier knows Alice's public key pk_A

2.2.2 Postconditions

- Alice knows all the messages have been successfully sent to someone
- Alice doesn't know the identity of the receiver
- Alice doesn't know whether the message will be eventually deliver to Bob
- Courier knows the integrity of the message is preserved
- Courier knows the authenticity of origin of Alice's messages

2.2.3 Message Sequencing Chart



2.2.4 Specification

Before the start of the protocol, Courier should randomly creates a symmetric key k_C which will be sent to Alice and used for deniable authentication later. Then Courier actively connects to Alice and sends first message to Alice. The first message should contain (1) The $\mathcal{ID}$ of Courier, (2) The maximum storage size of Courier, (3) Random key k_C encrypted by Alice's public key.

Once Alice receives the first message from Courier, it prepares for sending the

second message as reply. Firstly, Alice creates a random symmetric key k_{AB} which is supposed to be used as the session key with the message recipient Bob. Then Alice prepares the Meta block and its digital signature block MetaS. The Meta block contains meta information of the message content for Bob and it is encrypted under the public key of Bob. The plaintext of Meta block contains (1) Symmetric key k_{AB}, (2) The $\mathcal{ID}$ of Alice, (3) The $\mathcal{ID}$ of Bob, (4) A timestamp indicates the time Alice creates this message. To prove the authenticity of Meta block, Alice creates a digital signature of Meta block and encrypts the signature with k_{AB} which forms MetaS block.

After Alice has Meta and MetaS blocks, it creates a Msg block which is the encrypted message content for Bob under k_{AB}. Similarly, to ensure the integrity of the Msg block, a MAC of Msg block is created under k_{AB}, called MsgM block.

After Alice gets above 4 blocks, it creates a Infos block which is the whole information for Courier. Infos block is the concatenation of (1) The $\mathcal{ID}$ of Alice, (2) The $\mathcal{ID}$ of Bob, (3) Meta block, (4) MetaS block, (5) Msg block, (6) MsgM block. Then Alice appends a MAC of the Infos block to ensure its integrity. The MAC key is k_C, which can be revealed by decrypting $\mathcal{E}_{pk_A}(\mathrm{k}_C)$ in the first received message. Finally Alice examines the size of Infos block. If the total size of Meta, MetaS, Msg, MsgM blocks exceeds the storage limitation of Courier, it either reduces the size of those blocks and prepares them again, or reports an error and aborts the protocol. If it doesn't, Alice sends the whole message 2 which contains Infos block and its MAC, to Courier.

Once Courier receives the message 2 from Alice, it should check the validity of message 2. It first verifies $\mathcal{MAC}_{k_C}(\mathrm{Infos})$, if true then checks the $\mathcal{ID}$ of Alice to see if it is indeed the entity it is going to connect. After that, it checks the total size of the Meta, MetaS, Msg and MsgM blocks, making sure it does not exceeds the storage limitation. If any of above checks violate, Courier should report an error and abort the protocol. If all checks success, Courier uses k_C to create a MAC of the whole message 2 received from Alice and sends it to Alice as message 3.

At the end of the protocol, Alice checks the validation of message 3. It verifies the received MAC using k_C. If it verifies true, it means the protocol success and all postconditions are held. Otherwise, the protocol fails. However, the verification result does not prove the fact whether Courier has received the correct message 2 or not. Alice only knows its message may or may not be successfully sent. So further actions can be taken by Alice such as waiting for next Courier to send the same message or report an error.

2.3 Transmit Protocol

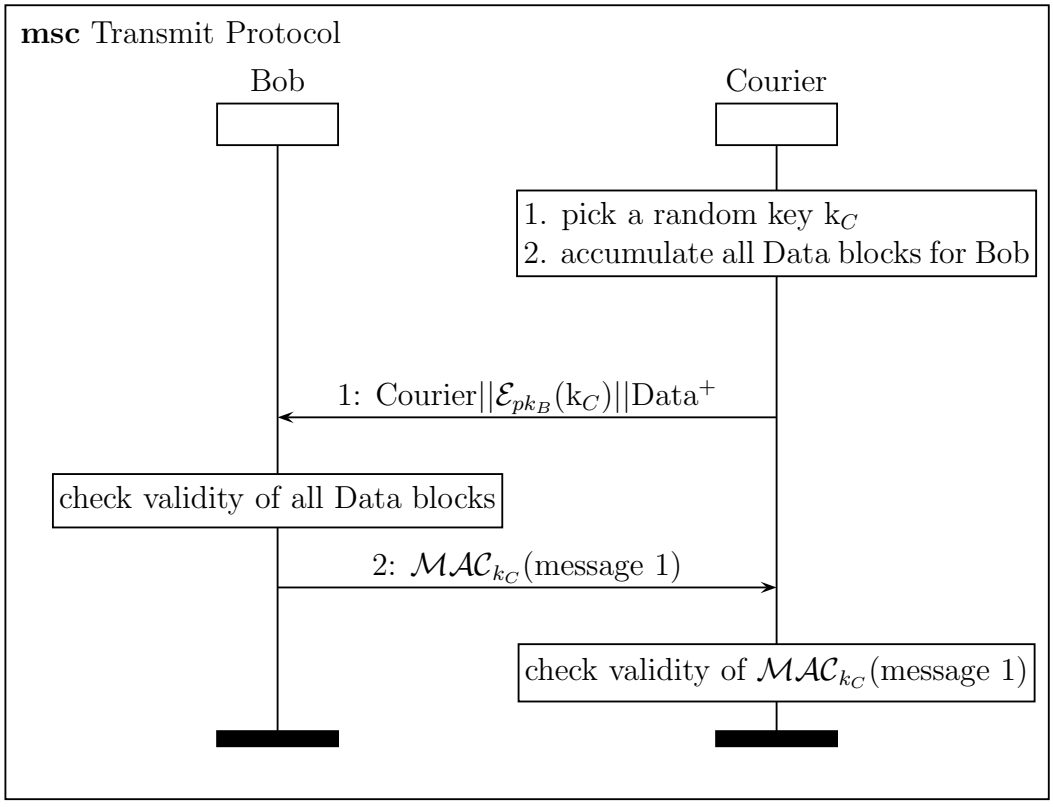
2.3.1 Preconditions

- Bob holds a unique pair of asymmetric key (pk_B, sk_B)
- Courier knows Bob's public key pk_B

2.3.2 Postconditions

- Bob accepts the message, knowing it is created by Alice
- Bob doesn't know the identity of the message sender
- Courier knows Bob has successfully received and accepted the message

2.3.3 Message Sequencing Chart



where:

Data = Meta||MetaS||Msg||MsgM

Meta = $\mathcal{E}_{pk_B}$(k$_{AB}$||Alice||Bob||timestamp)

MetaS = $\mathcal{E}_{k_{AB}}(\mathcal{SIGN}_A$(Meta))

Msg = $\mathcal{E}_{k_{AB}}$(message content)
MsgM = $\mathcal{MAC}_{k_{AB}}$(Msg)

2.3.4 Specification

Before start of the protocol, Courier first creates a random symmetric key k_C which will be sent to Bob and used for deniable authentication. Once Courier has k_C, it could prepare the data for Bob. By the time Courier starts the Transmit Protocol with Bob, it should have carried certain pieces of data for Bob which are collected earlier. As introduced in Submit Protocol, each piece of data from Alice contains (1) Meta block, (2) MetaS block, (3) Msg block, (4) MsgM block. We call such a piece of data a Data block. Courier now fetches all those data, and accumulate them together, forming a Data$^+$ block. Then Courier actively connects to Bob and sends the first message to Bob. The message 1 contains (1) The $\mathcal{ID}$ of Courier, (2) Random key k_C encrypted by Bob's public key, (3) The accumulation of all Data blocks for Bob.

Upon receipt of the first message, Bob checks the validity of all Data blocks received. Specifically, for checking every single Data block, it should do the following steps:

1. use sk_A to decrypt Meta, and reveal k_{AB}, message creator's ID, message recipient ID and timestamp.
2. check if message recipient ID is Bob itself and check timestamp to see if this message is expired.
3. use k_{AB} to decrypt MetaS and reveal $\mathcal{SIGN}_A$(Meta).
4. verify $\mathcal{SIGN}_A$(Meta) using pk_A.
5. verify MsgM using pk_A.
6. use pk_A to decrypt Msg and reveal the message content.

If any violation occurs during the checking or verification in certain Data block, Bob just discards the Data block and continues checking other blocks if there is any.

After all Data blocks have been received and checked, Bob send back a MAC of whole message 1 received from Courier. The key used for creating the MAC is k_C which is revealed by decrypting $\mathcal{E}_{pk_B}(\mathrm{k}_C)$ in message 1.

Finally Courier checks the validation of message 2. It verifies the received MAC using k_C. Same to the Submit Protocol, if the last MAC is verified true, it means

the protocol success and all postconditions are held. Otherwise, the protocol fails. However, the verification result does not prove the fact whether Bob has received the correct message 2 or not. Courier only knows its message may or may not be successfully sent. So further actions can be taken by Courier such as restart the protocol again or report an error.

Chapter 3

Security Analysis

3.1 Protocol Properties

Following are the properties that claimed to be held by CDSP, they are briefly introduced in this section and then will be proved afterwards.

3.1.1 Submit protocol

- **$\mathcal{A}$ is authenticated to $\mathcal{CR}$**
  As it has been assumed that physical transportation for a Courier is extremely costly, Courier should not carry messages for any arbitrary entity. It is expected that Courier only carries messages for those entities that have been authorized, so $\mathcal{A}$ should prove its identity when submitting the message.

- **The Integrity of message from $\mathcal{A}$ to $\mathcal{CR}$ is preserved**
  It is expected that the message is not modified or forged after being submitted to Courier.

- **$\mathcal{CR}$ is not able to access the message content**
  As the message content from $\mathcal{A}$ to $\mathcal{B}$ is highly confidential, it should not be disclosed to any other entity other than $\mathcal{B}$. Thus making message content inaccessible to $\mathcal{CR}$ prevents the content from being released when adversary examining the Courier's data.

- **$\mathcal{A}$ is able to deny sending any message to $\mathcal{CR}$**
  In certain scenarios which require high privacy protection - like exchanging military intelligence or voting, the action of sending out a message itself might become a sensitive information. It is expected that this protocol protects the

privacy of entity $\mathcal{A}$ in such a way that it can deny ever sending message to Courier at any time.

3.1.2 Transmit protocol

- **$\mathcal{B}$ is authenticated to $\mathcal{CS}$**
  As physical transportation is costly for Courier, Courier should not transmit its data to some arbitrary entity. It is reasonable that Courier ensures the message is transmitted to the target entity $\mathcal{B}$. Thus $\mathcal{B}$ should prove its identity when receiving data from Courier.

- **The Integrity of message from $\mathcal{CS}$ to $\mathcal{B}$ is preserved**
  It is expected that the message is not modified or forged after being transmitted to $\mathcal{B}$.

- **$\mathcal{B}$ is able to deny receiving any message from $\mathcal{CS}$**
  Similar to the Submit Protocol, in some privacy-sensitive scenarios, it is plausible for $\mathcal{B}$ to deny the fact of receiving data from Courier.

3.1.3 On the whole

- **$\mathcal{A}$ is authenticated to $\mathcal{B}$**
  As this CDSP is for sending message from $\mathcal{A}$ to $\mathcal{B}$, it is required that the message sender proves its identity to the recipient. Otherwise malicious Courier would be able to forge arbitrary messages to $\mathcal{B}$ that never exists.

- **Confidentiality of message from $\mathcal{A}$ to $\mathcal{B}$ is preserved**
  As the message content from $\mathcal{A}$ to $\mathcal{B}$ is highly confidential, it should not be disclosed to any other entity other than $\mathcal{B}$.

- **Integrity of message from $\mathcal{A}$ to $\mathcal{B}$ is preserved**
  It is expected that the message is not modified or forged during the transportation.

- **$\mathcal{A}$ can not deny sending a message to $\mathcal{B}$**
  This property is not deliberately designed in the protocol, it can be regarded as an auxiliary property as full deniability can not be achieve in an one-way authenticated communication. Despite of that, this property could still be meaningful for $\mathcal{B}$, as it proves the number of messages sent from $\mathcal{A}$.

- **$\mathcal{A}$ is able to deny the message content for $\mathcal{B}$**
  In some privacy-sensitive scenarios, it is reasonable for $\mathcal{A}$ to be able to deny the message content it has sent. According to above property, $\mathcal{A}$ is not allowed to fully deny sending a message to $\mathcal{B}$, however, capability of denying the message content has approximately the same effect, because $\mathcal{A}$ can always argue that the message content is empty.

3.2 Property Proof

3.2.1 Primitives

Before defining the system model, all the cryptographic primitives used and their corresponding notations in this protocol should be described:

- Message Authentication Code $\mathcal{MAC}$
  The MAC function used in this protocol is assumed to be secure in the sense that it has all the properties that a cryptographic hash function possesses and additionally, it resists to existential forgery under chosen-plaintext attack. That is, even if attacker is able to access an oracle which possesses the secret key and generates MACs according to the attacker's input, it is computational infeasible for attacker to guess MACs of other messages (not used to query the oracle).

- Signature Function $\mathcal{SIGN}$
  The signature function used in this protocol is assumed to be secure in the sense that it resists existential forgery under an adaptive chosen message attack. [**?**]

- Encryption Function $\mathcal{E}$ and Decryption Function $\mathcal{D}$
  To assure the security primitives of this protocol, all encryption/decryption schemes used are required to be secure in the sense that without the decryption key, it is computational infeasible for attackers to reveal the plaintext of a cipher with non-negligible probability.

- Symmetric Key Generator $\mathcal{G}$
  The symmetric key generator used in this protocol is assumed to be no less secure than a Cryptographically Secure Pseudorandom Number Generator. That is:
  (a)It should satisfy the next-bit test. That is, given the first k bits of a random sequence, there is no polynomial-time algorithm that can predict the (k+1)th bit with probability of success better than 50%.

(b)It should withstand "state compromise extensions". In the event that part or all of its state has been revealed (or guessed correctly), it should be impossible to reconstruct the stream of random numbers prior to the revelation. Additionally, if there is an entropy input while running, it should be infeasible to use knowledge of the input's state to predict future conditions of the CSPRNG state.
Furthermore, the keys generated are required to fit the Symmetric Encryption Scheme described above.
(cite: from wikipedia)

3.2.2 Submit protocol

THEOREM 1: $\mathcal{A}$ is authenticated to $\mathcal{CR}$
$Proof$:

Assuming $\mathcal{G}$ is secure, then $\mathcal{CR}$ is the only entity who knows the randomly generated key k_C. Providing $\mathcal{E}_{pk_A}$ scheme is secure, because k_C is encrypted by pk_A before sent out $\mathcal{A}$ will be the only entity who can reveal the encrypted k_C. Similarly, providing $\mathcal{MAC}$ scheme is secure, $\mathcal{A}$ is also the only one who can create MESSAGE 2 and its $\mathcal{MAC}_{k_C}$. Thus when (MESSAGE 2, $\mathcal{MAC}_{k_C}$) pair is received by $\mathcal{CR}$ and is verified true, it can be sure this message is created by $\mathcal{A}$. So $\mathcal{A}$ is authenticated to $\mathcal{CR}$.

THEOREM 2: The Integrity of message from $\mathcal{A}$ to $\mathcal{CR}$ is preserved
$Proof$:

Assuming $\mathcal{MAC}$ scheme is secure, any modification of MESSAGE 2 will lead to unpredictable changes in the $\mathcal{MAC}_{k_C}$(MESSAGE 2) and cause its verification to be false. And according to THEOREM 1, no one else but $\mathcal{A}$ can create the message and its valid MAC, message forgery is prevented. As consequence, the message integrity is preserved.

LEMMA 1 The message content cannot be revealed by any entity but $\mathcal{B}$
$Proof$:

Assuming $\mathcal{G}$ is secure, the randomly generated key k_{AB} is only held by $\mathcal{A}$. k_{AB} is encrypted by $\mathcal{E}_{pk_B}$ and sent to $\mathcal{CR}$, so assuming the $\mathcal{E}$ scheme is secure, only $\mathcal{B}$ can decrypt the cipher and reveal k_{AB}. As message content is encrypted by $\mathcal{E}_{k_{AB}}$, the only entity can decrypt it is $\mathcal{B}$ because only it knows k_{AB} (other than the message creator). Consequently, only $\mathcal{B}$ can reveal the message content created by $\mathcal{A}$.

THEOREM 3: $\mathcal{CR}$ is not able to access the message content
Proof :

According to LEMMA 1, only $\mathcal{B}$ can reveal the message content, we can easily deduce that $\mathcal{CR}$ is not able to reveal the message content.

THEOREM 4: $\mathcal{A}$ is able to deny sending any message to $\mathcal{CR}$
Proof :

The whole message sent from $\mathcal{A}$ to $\mathcal{CR}$ contains three parts - (1) entity IDs, (2) encrypted message from $\mathcal{A}$ and (3) $\mathcal{MAC}_{k_C}$, if $\mathcal{CR}$ wants to prove the authenticity of the origin of the whole message, it must show that at least one of these three parts can be created only by $\mathcal{A}$. However, all these three parts are forgeable by $\mathcal{CR}$ itself:

1. entity IDs are plaintexts, thus can be created by $\mathcal{CR}$.
2. as has been proven in LEMMA 1, no entity but $\mathcal{B}$ can reveal the securely generated key k_{AB}, so $\mathcal{CR}$ is not able to reveal $\mathcal{SIGN}_{\mathcal{A}}$ or message content, thus the encrypted message is just a block of random data for $\mathcal{CR}$, thus can be created by $\mathcal{CR}$.
3. $\mathcal{MAC}_{k_C}$ can also be created by $\mathcal{CR}$ because $\mathcal{CR}$ has k_C and is able to forge the whole former message.

To sum up, $\mathcal{CR}$ is able to create the whole message itself, it can not convince others the authenticity of the origin of the the message, so $\mathcal{A}$ is able to deny sending the message to $\mathcal{CR}$.

3.2.3 Transmit Protocol

THEOREM 5: $\mathcal{B}$ is authenticated to $\mathcal{CS}$
Proof :

Similar to proof of THEOREM 1, providing $\mathcal{G}$ and $\mathcal{E}$ scheme are secure, only $\mathcal{B}$ knows the symmetric key generated by $\mathcal{CS}$. So, assuming $\mathcal{MAC}$ scheme is secure, if $\mathcal{MAC}_{k_C}$(MESSAGE 1) can be successfully verified by $\mathcal{CS}$, it must be $\mathcal{B}$ who create the MAC. Thus, $\mathcal{B}$ is authenticated to $\mathcal{CS}$.

THEOREM 6: The Integrity of message from $\mathcal{CS}$ to $\mathcal{B}$ is preserved
Proof :

Similar to proof of THEOREM 2, any modification on MESSAGE 1 will leads to unpredictable changes in its MAC, and no one else but $\mathcal{B}$ can create the verifiable

MAC of arbitrary message. So if $\mathcal{MAC}_{k_C}$(MESSAGE 1) is verified true by $\mathcal{CS}$, it means it is originally created by $\mathcal{B}$ and has not been modified. Thus the message integrity is preserved.

THEOREM 7: $\mathcal{B}$ is able to deny receiving any message from $\mathcal{CS}$
Proof :

Similar to the proof of THEOREM 4, the message from $\mathcal{B}$ is totally forgeable by $\mathcal{CS}$ because it creates the whole MESSAGE 1 and holds k_C, it can create $\mathcal{MAC}_{k_C}$(MESSAGE 1) by it own. Therefore $\mathcal{CS}$ cannot prove to others that the MAC is sent from $\mathcal{B}$, $\mathcal{B}$ can deny receiving any message from $\mathcal{CS}$.

3.2.4 On The Whole

THEOREM 8: $\mathcal{A}$ is authenticated to $\mathcal{B}$
Proof :

As $\mathcal{B}$ receives two pieces of data - Meta and Msg, the authentication will be done for both of them separately.

Meta: Because $\mathcal{B}$ can decrypt the encrypted Meta from $\mathcal{A}$, it can reveal the sender $\mathcal{ID}$ and k_{AB}, then it can further decrypt $\mathcal{E}_{k_{AB}}(\mathcal{SIGN}_A(\text{Meta}))$ to get $\mathcal{SIGN}_A(\text{Meta})$. Assuming $\mathcal{SIGN}$ scheme is secure, if $\mathcal{B}$ verifies the signature true under $\mathcal{A}$'s public key, $\mathcal{B}$ knows Meta can only be created by $\mathcal{A}$.

Msg: Assuming $\mathcal{G}$ and $\mathcal{E}$ scheme is secure, only $\mathcal{B}$ can decrypt $\mathcal{E}_{k_{AB}}(k_{AB})$ and reveal k_{AB} in Meta. Thus only $\mathcal{B}$ (other than $\mathcal{A}$) can create $\mathcal{MAC}_{k_{AB}}$(Msg). So, if (Msg, $\mathcal{MAC}_{k_{AB}}$) pair is verified true by $\mathcal{B}$, $\mathcal{B}$ knows Msg is created by $\mathcal{A}$.

To sum up, $\mathcal{A}$ is authenticated to $\mathcal{B}$ as all message sent by $\mathcal{A}$ is authenticated.

THEOREM 9: Confidentiality of the message from $\mathcal{A}$ to $\mathcal{B}$ is preserved
Proof :

As proven in THEOREM 3, the message content from $\mathcal{A}$ to $\mathcal{B}$ can not be revealed by any other entities but $\mathcal{B}$, even the Courier itself. So after physical transportation and transmitting message to $\mathcal{B}$, this property still hold. This means only the creator and recipient of the message can reveal its content, so the confidentiality if preserved.

THEOREM 10: Integrity of the message from $\mathcal{A}$ to $\mathcal{B}$ is preserved
Proof :

Similar to the proof of THEOREM 6, assuming $\mathcal{G}$ and $\mathcal{E}$ scheme is secure, $\mathcal{B}$ is the only entity who can decrypt $\mathcal{E}_{k_{AB}}(k_{AB})$ and reveal k_{AB}. So when message is received by $\mathcal{B}$, only $\mathcal{A}$ and $\mathcal{B}$ hold k_{AB} and are able to create $\mathcal{MAC}_{k_{AB}}(\text{Msg})$. So any forgery will lead to MAC verification fail. Further more, if the Msg is modified, it will lead to unpredictable changes in $\mathcal{MAC}_{k_{AB}}(\text{Msg})$ and fail the MAC verification as well. So if (Msg, $\mathcal{MAC}_{k_{AB}}(\text{Msg})$) pair is verified true, the Msg must be created by $\mathcal{A}$, and remain unchanged. Thus the integrity of message from $\mathcal{A}$ to $\mathcal{B}$ is preserved.

THEOREM 11: $\mathcal{A}$ can not deny sending the message to $\mathcal{B}$
Proof :

Similar to the proof of THEOREM 8, if $\mathcal{SIGN}_{\mathcal{A}}$ is verified true, it proves the authenticity of the origin of the Meta, so $\mathcal{A}$ can not deny sending the message.

THEOREM 12: $\mathcal{A}$ is able to deny the message content sent to $\mathcal{B}$
Proof :

The message content contains two parts - (1) encrypted message $\text{Msg} = \mathcal{E}_{k_{AB}}(\text{message})$ and (2) its MAC $\mathcal{MAC}_{k_{AB}}(\text{Msg})$. Because k_{AB} is contained in the Meta and Meta is encrypted under $\mathcal{B}$'s public key, $\mathcal{B}$ is able to reveal k_{AB}. Then the whole message content part sent from $\mathcal{A}$ is forgeable by $\mathcal{B}$:

1. Msg is encrypted under k_{AB}, $\mathcal{B}$ can create any Msg it wants.
2. $\mathcal{MAC}_{k_{AB}}(\text{Msg})$ also can be created $\mathcal{B}$ because $\mathcal{B}$ can create Msg and hold k_{AB}.

As $\mathcal{B}$ can create the whole content part by its own, $\mathcal{B}$ can not prove to others that the message is from $\mathcal{A}$. Thus $\mathcal{A}$ can deny the message content for $\mathcal{B}$.

Chapter 4

Protocol Implementation

4.1 Application Overview

To run this protocol in a practical scenario, at least 3 different devices are required - one be Alice, one be Bob and one be Courier. This application implements all 3 entities within it, so once the device has this application, it can be any entity in the protocol. To achieve this, at the start of the application, user is asked to choose a particular role for the device to be. There are 4 options:

1. **DataCreator**, who creates message and wants to send it out.
2. **CourierReciever**, who connects to DataCreator and receives the message from it.
3. **DataReceiver**, who is the recipient of DataCreator.
4. **CourierSender**, who possesses the message from DataCreator and should transmit it to DataReceiver.

Once the choice has been made, the graphical user interface will adjust to the selected role, and user will be requested to input some information related to the selected role.

Below is a snapshot of the GUI of the application, it shows all the selections and textfields that will be used when the application interacts with user.

To run Submit Protocol, Alice should choose to run as DataCreator and Courier should choose to run as CourierReceiver. Then Courier transports to Bob and chooses to run as CourierSender, meanwhile Bob should choose to run as DataReceiver to run Transmit Protocol with Courier. The detailed instruction of how to run those two sub-protocols is given in the appendix.

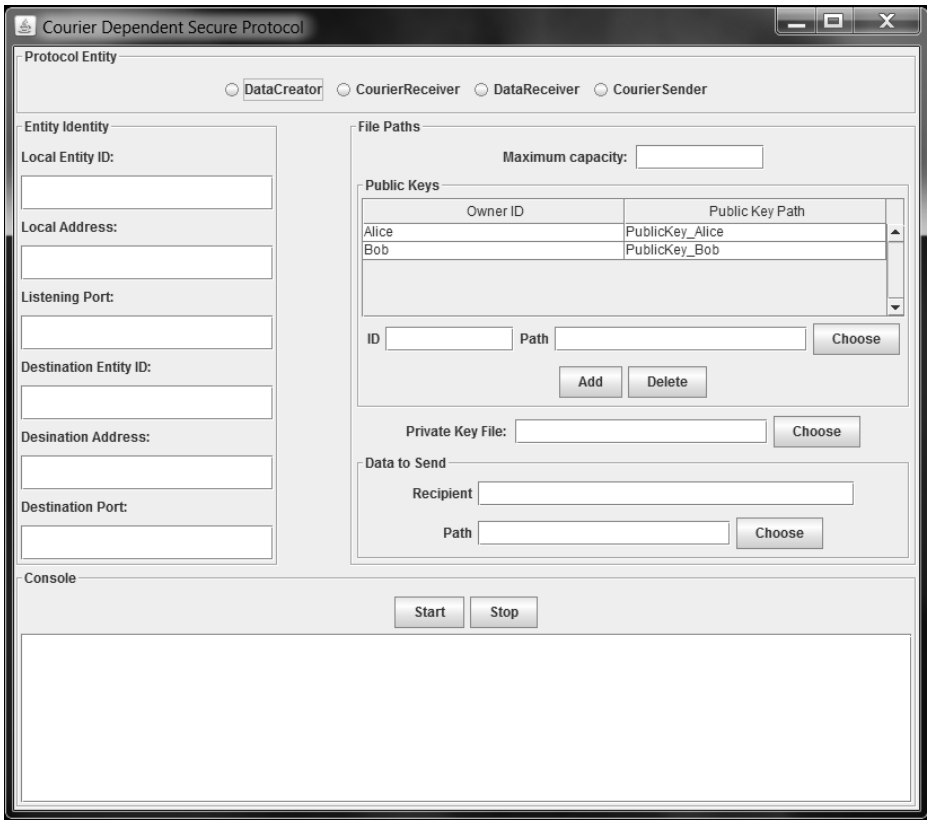


Figure 4.1: GUI Overview

To further illustrate how user can interact with the system, a use case diagram is given and every use cases appear in the diagram will be explained. For disambiguating, the "Alice", "Bob" and "Courier" appeared in the use case diagram do not mean the protocol entity as introduced in the system model, but are the names of the actors who control the device. The name of the actor simply reflects which entity the actor wants to be in the protocol.

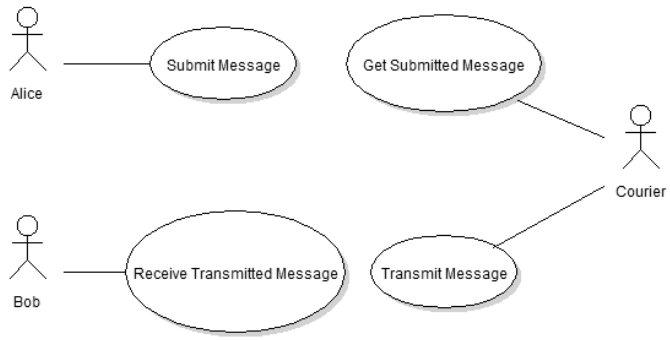


Figure 4.2: Use Case Diagram

Use Case 1: Submit Message

Title	Submit Message
Primary Actor	Alice
Goal in Context	Alice tries to submit the message to a Courier
Scope	System (Black Box)
Level	
Stakeholders	Alice and Courier
Success Guarantees	Message is received by Courier and Alice confirms the fact
Trigger	Alice starts the Submit Protocol
Main Success Scenario	1. Alice starts the application. 2. Alice selects "DataCreator" as the protocol entity in the application. 3. Alice specifies all related information as instructed in the "Run Submit Protocol" section. 4. Alice starts running the protocol.

Use Case 2: Get Submitted Message

Title	Get Submitted Message
Primary Actor	Courier
Goal in Context	Courier tries to obtain the message of Alice
Scope	System (Black Box)
Level	
Stakeholders	Courier and Alice
Success Guarantees	Courier gets a message from Alice
Trigger	Courier starts the Submit Protocol
Main Success Scenario	1. Courier starts the application. 2. Courier selects "CourierReceiver" as the protocol entity in the application. 3. Courier specifies all related information as instructed in the "Run Submit Protocol" section. 4. Courier starts running the protocol.

Use Case 3: Receive Transmitted Message

Title	Receive Transmitted Message
Primary Actor	Bob
Goal in Context	Bob tries to receive message of Alice carried by Courier
Scope	System (Black Box)
Level	
Stakeholders	Bob and Courier
Success Guarantees	Bob receives the message
Trigger	Bob starts the Transmit Protocol
Main Success Scenario	1. Bob starts the application. 2. Bob selects "DataReceiver" as the protocol entity in the application. 3. Bob specifies all related information as instructed in the "Run Transmit Protocol" section. 4. Bob starts running the protocol.

Use Case 4: Transmit Message

Title	Transmit Message
Primary Actor	Courier
Goal in Context	Courier tries to transmit Alice's message to Bob
Scope	System (Black Box)
Level	
Stakeholders	Courier and Bob
Success Guarantees	Message is received by Bob and Courier confirms the fact
Trigger	Courier starts the Transmit Protocol
Main Success Scenario	1. Courier starts the application. 2. Courier selects "CourierSender" as the protocol entity in the application. 3. Courier specifies all related information as instructed in the "Run Transmit Protocol" section. 4. Courier starts running the protocol.

4.2 Software Design

The implementation of this protocol mainly consists of two parts - a core library and an user interface. The core library defines the framework of the program and provides

all essential components for running the protocol. While the user interface takes user's input, configures components provided by the core library, runs the protocol and outputs running results if necessary. This design separates the implementation of user interfaces from the actual running of the protocol, the major benefit is that when this protocol is running on different devices or platforms, its user interfaces can be customized and easily plugged to the core library without modifying it.

4.2.1 Program Architecture

As introduced above, the whole program contains 4 roles - DataCreator, DataReceiver, CourierSender and CourierReceiver. Classfied by their main structure, those 4 different roles fall into 2 categories - (1) Accepter, who continuously listens to the port and waits for incoming connection. (2) Initiator, who actively connects to a Accepter. Although these two categories sounds similar to Client-Server pattern, it is not quite the case because Accepter does not actually provide any service. Based on their behaviour definition in protocol specification, DataCreator and DataReceiver belong to Accepter, while CourierSender and CourierReceiver belong to Initiator. Following paragraphs will introduce the internal architecture for Accepter and Initiator respectively.

Accecpter Accepter contains 5 main parts:

- Dispatch Thread
  The Dispatch Thread listens to the program port, waits for incoming connections. Once it receives a connection, it will create a new session, then handover the connection to the newly created session. After that, it will continue listening to the port, wait for next incoming connection.

- Sessions
  Sessions are created by the Dispatch Thread, each session corresponds to a single connection and sessions are independent between each other. Once a session takeovers a connection, it is fully responsible for it. Inside a session there is a Delegate and a Sub-thread.

  The **Delegate** defines all communication content (e.g. a Delegate of Alice defines the content of messages to send out, and it also defines what to do when receives a certain message), it behaves like a state machine which takes message as input, processes the message and output a new message for response. During

the processing of input messages, it may interact with the 3 global objects - User Interface, Cryptographic Kit and Data Manager. The detail of Delegate will be explained in Delegate Model.

The **Sub-thread** listens to the connection which is handover by Dispatch Thread, capture any message from the connection. It delivers the captured message to Delegate, and receives a new message from Delegate. If the output message from Delegate does not indicate an exception or termination, the Sub-thread sends the message through the connection, otherwise it reports an error or terminates.

- User Interface
  The User Interface is shared between all sessions in Accepter. It displays all relative information to show the progress of the protocol running and reports errors to the user.

- Cryptographic Kit
  The Cryptographic Kit is shared between all sessions in Accepter. It provides functionalities of all cryptographic operations that is needed in the protocol, such as encryption, decryption, key generation, MAC generation and verification, and digital signature generation and verification. When any session need to do cryptographic operations, it just call from Cryptographic Kit and doesn't care the internal implementation. For the consistency concern, it is required that any two communicating device should use same Cryptographic Kit.

- Data Manager
  The Data Manager is shared between all sessions in Accepter. It keeps record of all data files in the device's disk which is related to the protocol, such as files of public keys, secret keys, and the message Courier carries. Data Manager is configured at the start of the application, when any session need data in disk, it just request from Data Manager.

The relation between those 5 components is illustrated in the figure "Accepter Architecture".

Initiator Similar to Accepter, Initiator consists of 4 main parts: (1) Session, (2) User Interface, (3) Cryptographic Kit and (4) Data Manager. The major difference between Initiator and Accepter is that Initiator does not have a Dispatch Thread, every Initiator only has one Session. The Session is created once the Initiator is

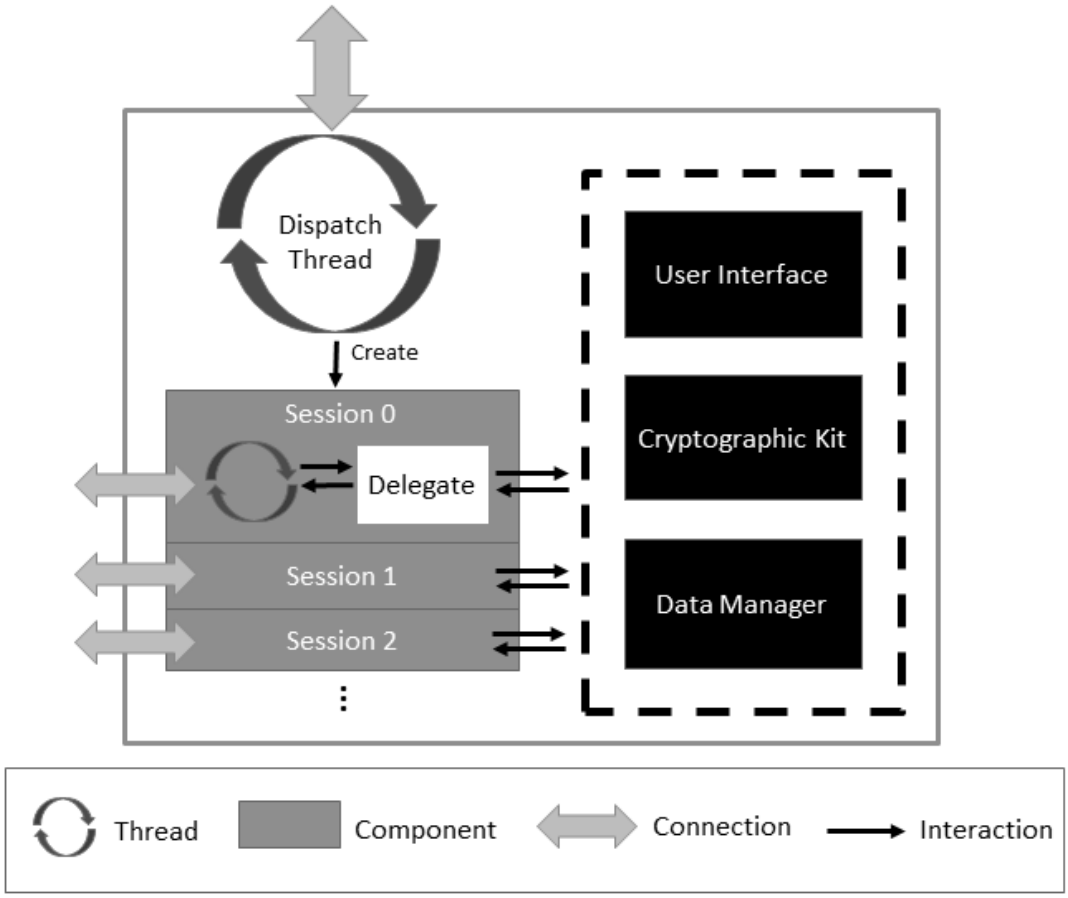


Figure 4.3: Accepter Architecture

started, and it will ask its Delegate for a "initial message" - which will be the first message of the protocol, and will be sent to the specified Accepter. The architecture design of Initiator is a simpler version of Accepter's, and it is illustrated in the figure "Initiator Architecture".

4.2.2 Delegate Model

The object Delegate is the essence of the application, it directly refers to the specification of the protocol, defines how an entity processes a message - here "process a message" may involve doing cryptographic operations, checking message content validity and giving a response message.

Basically, every Delegate acts like a finite-state machine, who possesses an internal state, takes messages as inputs and outputs new messages as response. The internal state controls the behaviour of the Delegate - Delegates in different states will respond

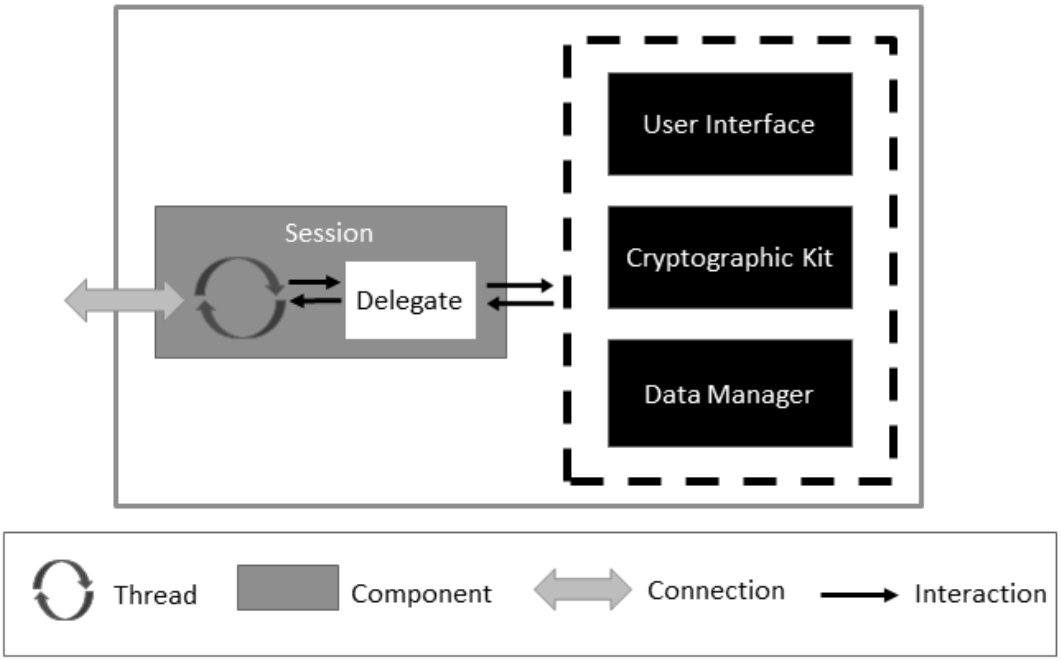


Figure 4.4: Initiator Architecture

differently to a same input. So when an input message comes, Delegate will process the message according to its current state, if the message is successfully processed, it will change its current state and wait for next message, until it reaches the final state.

Taking entity $\mathcal{A}$ as example,the figure below shows a 4-internal-state machine which abstracts the behaviour of $\mathcal{A}$: initially $\mathcal{A}$ is in Wait state, waiting for the first message. Once it receives the first message, it will process the message (according to the Submit Protocol, it will check the first message and submit its data to Courier). If $\mathcal{A}$ successfully processed M_0, it enters Submitted state, waiting for the second message. Then it will receive and process M_1 (according to the Submit Protocol, it will check the validity of the MAC). If it is successful again, it enters the final state Checked and stops. If any error occurs in processing the input messages in early states, $\mathcal{A}$ directly enters final state Error and stops.

4.2.3 Message Structure

Based on the protocol specification, there are totally 5 different kinds of messages to exchange in a single success protocol run - 3 messages are needed to achieve Submit

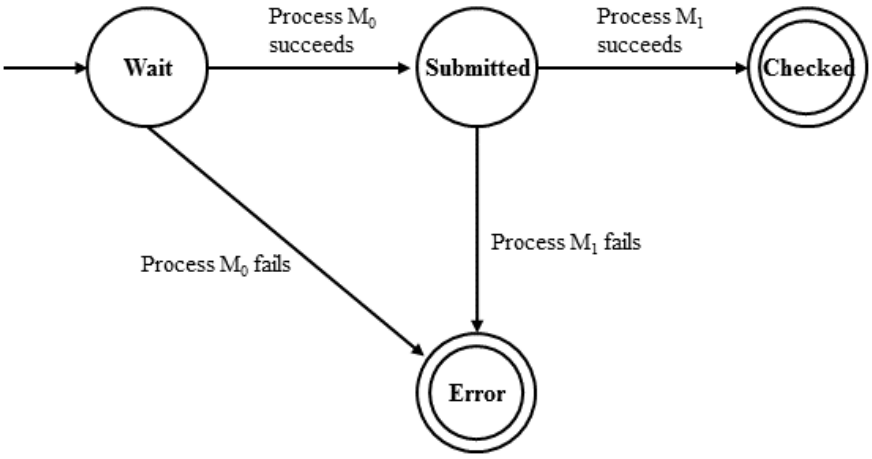


Figure 4.5: State Machine of $\mathcal{A}$

Protocol and 2 messages are needed to achieve Transmit Protocol. The design of message structure attempts to maximize the time efficiency of the protocol, thus no extra message will be exchanged and the lengths of messages will be minimized. All messages exchanged in this protocol are concatenations of 6 different kinds of primary blocks:

- **Integer Block**
  Integer Block simply contains a single Integer, it occupies 4 bytes (based on the current JAVA's Implementation).

- **MAC Block**
  MAC Block contains a cryptographic MAC, whose size is defined by the Cryptographic Kit the application uses.

- **Asymmetric Cipher Block**
  Asymmetric Block contains an asymmetric cipher. Because encrypting a long plaintext using asymmetric encryption takes long time, to reduce the computational consumption, the length of plaintext for asymmetric encryption is restricted in this protocol, so that only one cipher block will be produced after the encryption. As the consequence, the size of Asymmetric Cipher Block is fixed, which is 128 bytes (based on a key of size 128 bits).

- **ID Block**
  ID Block contains two parts. The front part is a single byte which indicates

the total length of the ID string and the following part is a string of characters representing the ID. The size of ID Block is variable, which is the length of ID string plus 1 bytes.

- **Meta Block**
  The Meta Block in application design is different with "Meta block" in protocol specification. It contains a concatenation of 3 parts - (1) an integer indicates the size of the rest of this Meta Block, (2) an asymmetric cipher of the meta of the message, (3) a symmetric cipher of the signature of the meta. As explained in Asymmetric Cipher Block, the size of all asymmetric ciphers is fixed, so the size of the asymmetric cipher is (size of Meta Block - size asymmetric cipher).

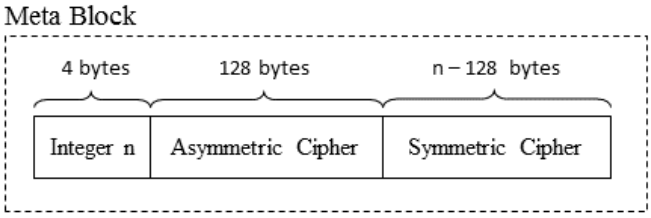


Figure 4.6: Structure of Meta Block

- **Message Block**
  The Message Block is also different with "Msg block" in protocol specification. Similar to Meta Block, it is the concatenation of 3 parts - (1) an integer indicates the size of the rest of this Message Block, (2) a symmetric cipher of the actual message content, (3) a MAC of the part (2). The size of symmetric cipher can also be deduced as the size of MAC is fixed.

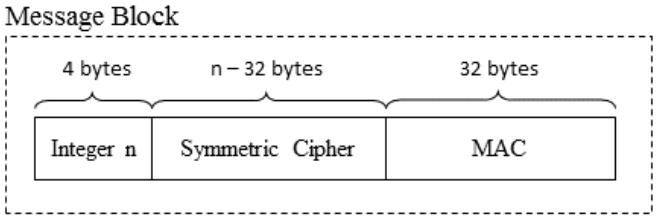


Figure 4.7: Structure of Message Block

To summarize, 3 of these 6 primary blocks are fixed-size blocks (Integer Block, MAC Block and Asymmetric Cipher Block), while other 3 of them are variable-size blocks (ID Block, Meta Block and Message Block). All the messages exchanged in the

protocol are constructed by these primary blocks through concatenation, and they will be illustrated below.

Submit Protocol

Message 1, from Courier to Alice:

ID Block	Integer Block	AC Block

Note that "AC Block" denotes Asymmetric Cipher Block.

Message 2, from Alice to Courier:

ID Block	ID Block	Meta Block	Message Block	MAC Block

Message 3, from Courier to Alice:

MAC Block

Transmit Protocol

Message 1, from Courier to Bob:

ID Block	AC Block	Meta_0	Message_0	Meta_1	Message_1	.....

Multiple Meta Blocks and Message Blocks can be appended here.

Message 2, from Bob to Courier:

MAC Block

Error Message Flag

There are two kinds of messages exchanged in the protocol, all above messages are one of them, called Normal Message, the others called Error Message. Those two kinds of messages are distinguished by an Error Message Flag, which is the first byte of the message. Thus there is an extra step before above Normal Messages to be sent - they should be wrapped by an extra byte 0 at the front of them. While an Error Message contains two parts - (1) a byte indicates the size of the rest of the message, (2) a string of error information. As consequence, all messages start with a byte 0 will be treated as Error Message. The figure below further illustrates the difference between Normal Message and Error Message.

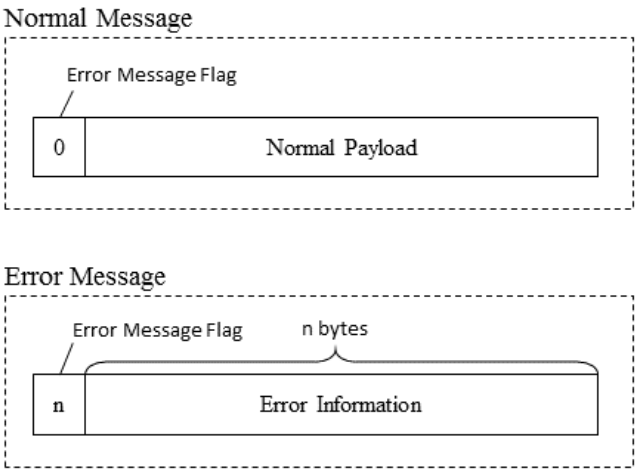


Figure 4.8: Normal Message and Error Message

4.3 Implementation Details

4.3.1 UML Class Diagram

A UML Class Diagram has been plotted to show all the main classes in the program and the relations between them.

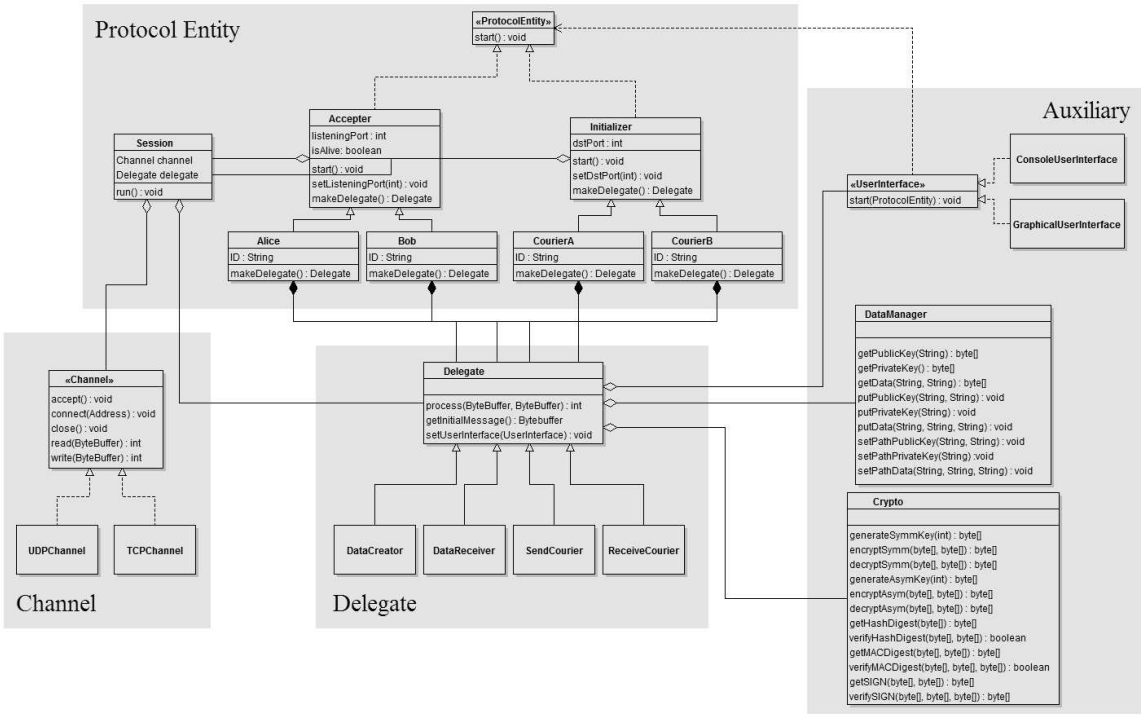


Figure 4.9: UML Diagram

According to the diagram, the whole program can be separated into 4 main parts:

- **Protocol Entity**
  This part defines the framework of this application. Any protocol entity can be first specified into an Accepter or an Initiator, then based on the role it plays, it can be further classified into a particular role like Alice, Bob, CourierA (Courier who connects to Alice) or CourierB (Courier who connects to Bob). As shown in the diagram, every level of classification corresponds to a group of classes and lower level classes inherit from the higher level classes. The main job of Protocol Entity classes is creating, initializing and managing its Session objects. While a Session class - which is possessed by every protocol entity, deals with the message transmission issues for the entity, such as requesting next messages from Delegate, sending messages to the Channel, etc.

- **Channel**
  The Channel is used in Session class, it is an Interface denotes a place where messages can be sent and received. Ideally, when two channels are connected, devices can easily push message in and receive message from their channels without awareness of any detail about the connection. However, due to different networks and protocols suites may be used when running CDSProtocol, various implementations of Channel are necessary. As shown in the diagram, possible implementations of Channel Interface can be TCPChannel and UDPChannel, corresponds to connecting under TCP or UDP. Except above two, even more different channels could be developed like BluetoothChannel, CableChannel, etc. In this prototype program, only UDPChannel is currently implemented and the detail of it will be explained in the later "Connection Establishment" section.

- **Delegate**
  As has been demonstrated in the "Delegate Model", Delegate class defines the "rule" of an entity. It takes a message as input, processes the message and outputs a responding message if there is one. However, Delegate is just an abstract notion, its children classes define the real "rules" of each entity respectively. As shown in the diagram, DataCreator, DataReceiver, CourierSender, CourierReceiver are 4 different implementations of Delegate class, they define the "rules" for the 4 entities correspondingly - Alice, Bob, CourierA and CourierB.

- **Auxiliary**
  This part contains 3 components that can be totally independent with the design of CDSProtocol. The UserInterface only deals with inputs from user and displays output to user. Reflect to the software design, its implementation can be various to fit different devices and platforms. The DataManager takes charge of managing the disk files that is related to the running of the protocol. And the Crypto represents "Cryptographic Kit" in the software design, its job is to provide all cryptographic operations that is needed in the protocol.

Extensibility and Reusability The design of the program structure attempts to maximize the extensibility and reusability of the program in order to make the program easy for modifying and extending after release. It should be noticed that all components of the program are loosely coupled which makes them easy for reuse, and frequently used inheritance and interfaces makes the program extensible. Developers can modify or create their own entities, delegates, channels or even cryptographic kits without affecting other parts of the code.

4.3.2 Connection Establishment

The Channel is used to establish connections between entities in program. Each Channel object is associated with a local address and listening port before connected. There are 2 steps for two entities to get connected using Channel. Firstly, Initiator initiates the connection by calling the connect() method of its Channel object, specifying the destination IP address. Then the Accepter accepts the connection by calling the accept() method of its Channel object. The accept() method will wait until there is a connection to accept and what it really does is creating a new Channel object which is connected to the incoming connection, and returns that newly created Channel object. Once the connection is accepted, both entities can use Channel's read() and write() method for receiving and sending messages. If any of the entity chooses to terminate the connection, it calls the close() method of its Channel, then both Channels are closed.

UDPChannel The above connecting mechanism is effective in this protocol, as the Channel object who accepts connections will not be connected to any Channel, thus it can accept several connections without changing its listening port - imaging if channel gets connected once it accepts a connection, then when a new connection comes, it will not be able to accept it. However, to implement this mechanism for

UDP requires extra effort because UDP itself is connectionless and every packet sent or received is independent between each other. The real process for establishing connections using UDPChannel is: When the Initiator calls the connect() method of its Channel object, the channel records the destination address and port number but sends nothing. So when Accepter calls accept() nothing will happen until Initiator sends the first message, at which point accept() will create a new Channel object with a different listening port and all future messages will be sent through this Channel object. So, when Accepter sends back the second message, the port number of the channel sending the message is different with what Initiator specified in the first message. So when Initiator receives a reply message fron Accepter, it changes its channel's destination port number to the coming channel's port number, so that its future messages will be sent to the Accepter's newly created channel. Finally the connection is built between Initiator's channel and Accepter's newly created channel.

4.3.3 Message Processing

When a message is received from the channels, it will be examined by the session first, where the Error Message Flag will be checked. If the Error Message Flag (the first byte of the received message) is greater than 0, it indicates the message is an Error Message and the number of the Error Message Flag represents is the length of the error information. Then session will extract the error information and displays it on the user interface. If the Error Message Flag is 0, it means the message is a Normal Message. Then session will extract the payload and feed it to the delegate. Delegate will further process the payload and returns an integer indicating the size of the responding message. If the integer is 0 it means the message is successfully processed and no further messages to be sent. If the integer is negative, it means an exception occurs during the processing.

When session gets a message from delegate, it should wrap it into a Normal Message by adding a 0 byte in the front of the message. Then session sends the wrapped message to the channel and waits for receiving next message from the channel.

4.3.4 Cryptographic operations

The cryptographic functions provided by the Crypto class in this program are mainly built from two Java packages "java.security" and "javax.crypto", thus the security of this application highly relies on the implementation inside those two Java packages. Below will list and explain all the cryptographic operations used in this protocol. As

there is no sign indicating there is any flaw inside the Java security packages, we will not dig too deep into the security cryptographic implementation.

- **Symmetric Encryption / Decryption / KeyGeneration**
  The symmetric encryption / decryption scheme used is AES. The mode of operation used is CBC. The padding scheme is PKCS#5. The size of key used is 128 bits and it should not exceed 936 bits.

- **Asymmetric Encryption / Decryption / KeyGeneration**
  The asymmetric encryption / decryption scheme used is RSA. The mode of operation used is ECB, however, for efficiency concern, the size cipher block of asymmetric encryption will be restricted to 1, so mode of operation will not actually be used in the program. Th padding scheme is PKCS#1. The size of key used is only 1024 bits, as this is only a prototype application and key size can easily be increased in future.

- **MAC Creation / Verification**
  The MAC algorithm used is Hmac-SHA-256. The size of key used is same to symmetric encryption / decryption, which is 128 bits.

- **Digital Signature Creation / Verification**
  The signature algorithm used is RSA. The cryptographic hash function used in SHA256. They key size is same to asymmetric encryption / decryption, which is 1024 bits.

4.3.5 File Management

It is assumed that adversary is not able to hack into its target entity's system, that is, the adversary can not access to the memory or disk of a honest entity's device. Based on this assumption, all the data files are stored explicitly in device's disk.

Keys As a single device is able to act as several different entities, it is possible that one device possesses several secret keys and presumably a long list of others' public keys. The user should take care of his/her own key files, and before the protocol starts, he/she specifies the locations of all keys. Then during running, the application will read those files when necessary.

Alice's Message Content Similar to the keys, Alice's message content should be stored in the disk of Alice's device. Before the start of the protocol, user will be requested to specify the location of that file. Then during Submit Protocol, the file will be read when necessary.

Courier's Payload Courier's payload files are not specified by user, it is managed by the application. For every Courier entity, it has a working directory, by default, Courier's working directory is in the application's directory, named after its ID. Once Courier gets data from Alice in Submit Protocol, it will save the data into its working directory, the file name will be the destination entity's ID. For example, if Courier0 receives data from Alice to Bob, the data will be saved in the file "./Courier0/Bob". As Courier may receives data from multiple datacreators, all further data will be appended to the file named after the receiver's ID, if no such file, program will create it. So, after the Message Acquisition phase, Courier may have several data files, and each contains data from multiple datacreators. Finally in Transmit Protocol, Courier transmits the corresponding data file to its destination entity base on the file name.

4.3.6 Error Handling

In this application, errors are classified into 4 main classes - user input error, I/O error, protocol error and timeout. Below will explain the details of these 4 errors and how they are handled in the program.

User Input Error User input errors occur when user input meaningless content into the application's textfield, such as inputing non-numeric string as port number, etc. This kind of errors will be caught before the protocol starts running, after user click "Start" button. Once user input error is detected, its detail will be sent to user interface where the error detail will be shown to the user.

I/O Error I/O error denotes errors happening when reading/write files or sending/receiving through network channels, such as files not found when reading files, or port number is in use when creating a network socket, etc. These errors are caught during the running of the protocol and will cause termination of the protocol run. Similar to user input error, once I/O error is detected, its detail will be sent to user interface and then be shown to the user.

Protocol Error Protocol error is produced by the protocol itself, when there is some checking violation happens such as verifying a MAC to false, or the message size exceeds the capacity of Courier's storage, etc. All the checking processes have been fully described in the protocol specification, and the program strictly follows those processes. Because all checking operations happen in delegates while delegates processing the received messages, the protocol error is detected by delegates. Once a protocol error is detected, firstly, the error detail will be sent to user interface and be shown to the user. Meanwhile, the delegate will return a negative integer indicating error happens during processing. Then session will send a Error Message to the other entity reporting the error. However, for the security concern, Error Message will not include any detail about the error, currently it just carries a string "Protocol Error".

Timeout Technically timeout is not an error but a mechanism of protecting an entity from waiting responses for too long time. And it is essential in this protocol because when an I/O error occurs during the protocol, it immediately terminates the program in this device, without reporting anything to the other device which still waits for reply. Timeout allows the other device to abort the protocol if no message is received after waiting for a certain amount of time. Timeout is detected in sessions. After sending out a message session will first check whether it is the end of the protocol, if it is, session will close the channel and terminate. If it is not, session will monitor the channel with a timer. Upon the time runs out, it will voluntarily close the channel and terminate.

Appendix A

Application Instruction

To start a protocol using this application involves 3 basic steps - (1) user chooses a specific protocol role. (2) user inputs the information related to the selected protocol role. (3) user starts the protocol. Below is a snapshot of current GUI of the application, it basically consists of 4 main panels:

- **Protocol Entity**
  It is on the very top. It provides 4 roles (as mentioned above) to be chosen for the user. Because every device runs this protocol must be one of those four roles, it is essential that user specifies a role in this panel before start running the protocol.

- **Entity Identity**
  It locates on the left. Here user specifies the information about the host device and the destination device, such like IDs, and IP addresses.

- **File Paths**
  It locates on the right. Here user manages all the disk files that are related to the running of the protocol. Presumably, many important information like public keys, private keys and messages are all files in the device's disk, user has to specify those files' paths before running the protocol.

- **Console**
  It is at the bottom. Here provides buttons for user to start and stop the protocol, and it displays information about the running protocol in a information board.

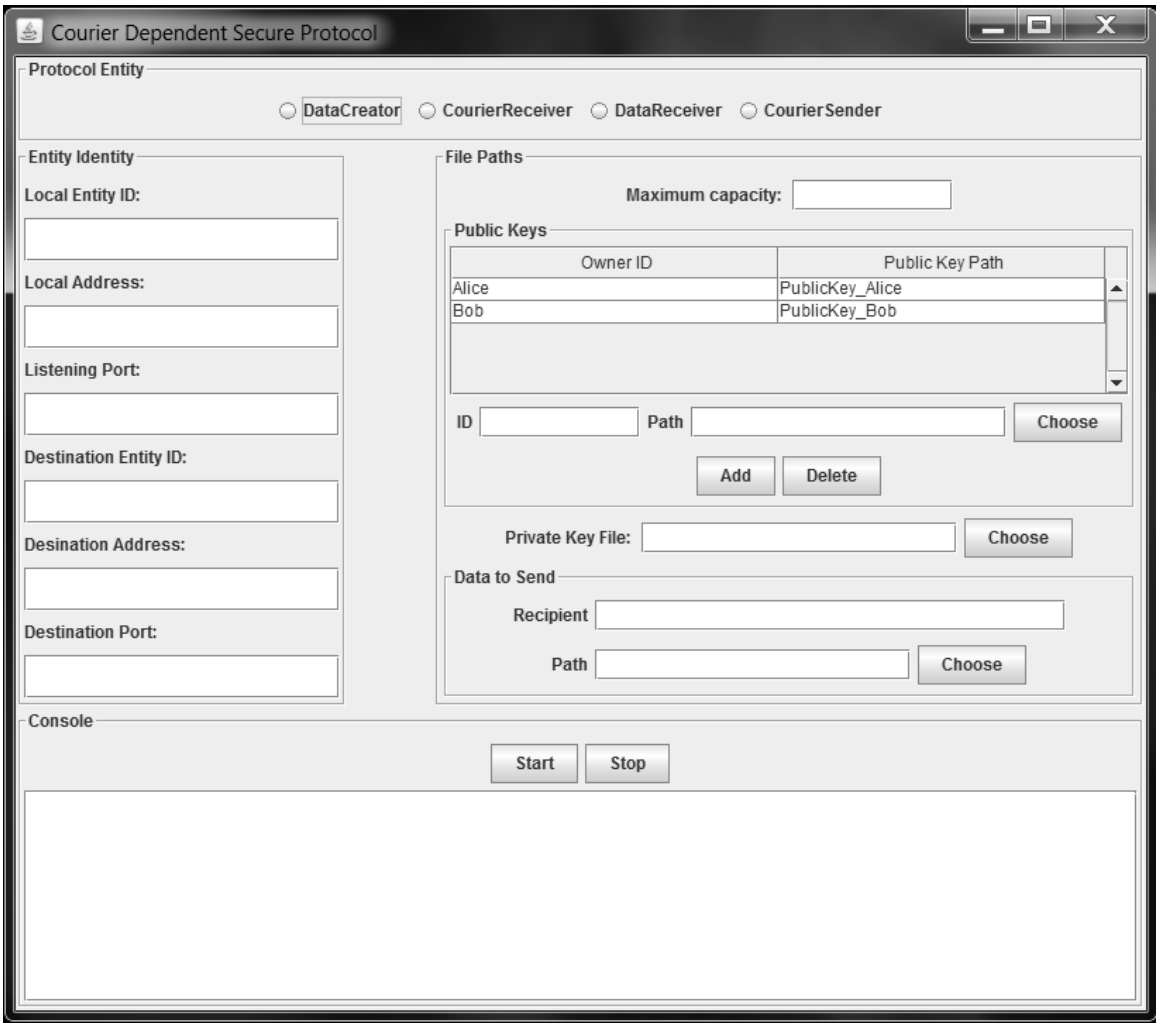


Figure A.1: GUI Overview

A.1 Run Submit Protocol

It requires at least 2 devices to run this protocol, we call them D_0 and D_1. Assume D_0 is entity Alice, who possesses a message and wants to send it to Bob. Assume D_1 is entity Courier, who is able to carry the message and transmit it to Bob. To run the protocol successfully, it should be done by the following procedure:

1. D_0 starts the application.
2. D_0 user selects "DataCreator" in the Protocol Entity panel.
3. D_0 user specifies the entity ID, local address and listening port (9888 by default) by filling the corresponding textfields in Entity Identity panel.

4. D_0 user adds destination entity's public key into its public key list.
   There are two ways to add an new entry to the public key repository:

   (a) Adding through application: input the ID of the public key holder and the path of public key file by filling the textfields in the Public Key panel. Then click Add button. The (ID, path) pair will then appear in the public key list. This effect is temporary, the pair will disappear in the next launch.

   (b) Adding through configuration file: by default, when application is launched, it will import all (ID, path) pairs from a file named PublicKeys in the current directory. User can appending a new line to PublicKeys file to add a new pair. The format is ID;Path, e.g. "Alice;/publickeys/alice.pk". This effect will take place since next launch of the application.

5. D_0 user specifies its private key by filling the textfield with the private key file.

6. D_0 user specifies recipient entity's ID by filling the textfield in the Data to Send panel.

7. D_0 user specifies the file that contains the message needs to be sent by filling the file path in the corresponding textfield.

8. D_0 user click Start button in the Console panel. The running progress of the protocol will be displayed in the information board in the Console panel.

9. D_1 starts the application.

10. D_1 user selects "CourierReceiver" in the Protocol Entity panel.

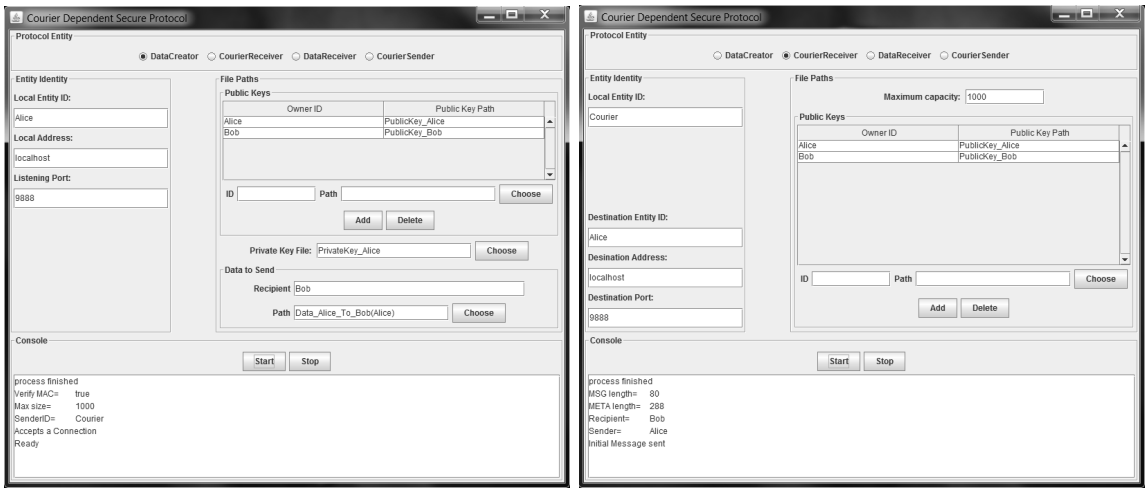
11. D_1 user specifies its own entity ID by filling the textfield in Entitiy Identity panel.

12. D_1 user specifies the ID of the entity he wants to contact (here D_0's ID), together with its address and port number by filling corresponding textfields in the rest of Entity Identity panel.

13. D_1 user add the public key of the entity he wants to contact into the public key list. The way of doing that has been introduced in step 4.

14. D_1 user click the Start button in the Console panel. The running progress of the protocol will be displayed in the information board in the Console panel.

Below figures show snapshot of two applications successfully running Submit Protocol. After application consoles on both devices pops "process finish" successfully, the message of D_0 has been submitted to the D_1, and is stored in the file named by the message recipient's ID. If D_1 gathers messages from multiple devices, all messages to the same recipient will be accumulated in the same file.



(a) DataCreator (b) CourierReceiver

Figure A.2: Running Submit Protocol

A.2 Run Transmit Protocol

It requires at least 2 devices to run this protocol, we call them D_1 and D_2. Assume D_1 is entity Courier, who possesses an encrypted message from Alice and wants to send it to Bob. Assume D_2 is entity Bob, who waits to receive message from Alice. The running procedure of Transmit Protocol is:

1. D_2 starts the application.
2. D_2 user selects "DataReceiver" in the Protocol Entity panel.
3. D_2 user specifies the entity ID, local address and listening port (8888 by default) by filling the corresponding textfields in Entity Identity panel.
4. D_2 user adds destination entity's public key into its public key list. The way of doing that has been introduced in the step 4 of running Submit Protocol.
5. D_2 user specifies its private key by filling the textfield with the private key file.

6. D_2 user click Start button in the Console panel. The running progress of the protocol will be displayed in the information board in the Console panel.

7. D_1 starts the application.

8. D_1 user selects "CourierSender" in the Protocol Entity panel.

9. D_1 user specifies its own entity ID by filling the textfield in Entitiy Identity panel.

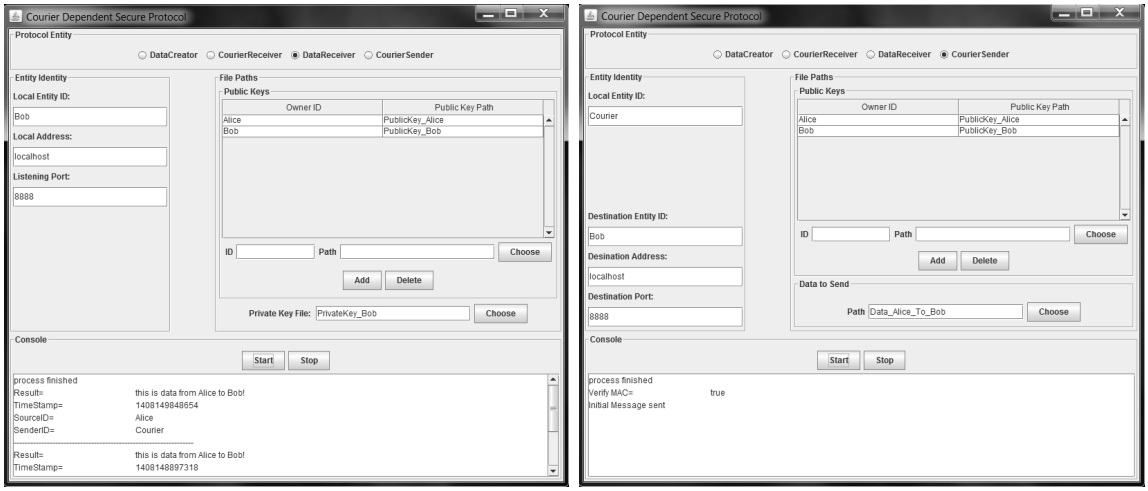
10. D_1 user specifies the ID of the entity he wants to contact (here D_2's ID), together with its address and port number by filling corresponding textfields in the rest of Entity Identity panel.

11. D_1 user add the public key of the entity he wants to contact into the public key list. The way of doing that has been introduced in step 4.

12. D_1 user specifies the file that contains the data needs to be sent, by filling the file path in the corresponding textfield in Data to Send panel.

13. D_1 user click the Start button in the Console panel. The running progress of the protocol will be displayed in the information board in the Console panel.

Below figures show snapshot of two applications successfully running Transmit Protocol. After application consoles on both devices pops "process finish" successfully, the data carried by D_1 has been transmitted to D_2. If the authenticity of the data is successfully verified, D_2 will print the message content out in the information board. If the data contains messages from multiple senders, they will be verified and printed one by one so that user knows which messages have been discarded.



(a) DataReceiver (b) CourierSender

Figure A.3: Running Transmit Protocol

References

[1] Albert Einstein. Zur Elektrodynamik bewegter Körper. (German) [On the electrodynamics of moving bodies]. *Annalen der Physik*, 322(10):891–921, 1905.