A New Knapsack Public-Key Cryptosystem Based on Permutation Combination Algorithm

Min-Shiang Hwang, Cheng-Chi Lee, and Shiang-Feng Tzeng

Abstract—A new secure knapsack cryptosystem based on the Merkle-Hellman public key cryptosystem will be proposed in this paper. Although it is common sense that when the density is low, the knapsack cryptosystem turns vulnerable to the low-density attack. The density \( d \) of a secure knapsack cryptosystem must be larger than 0.9408 to avoid low-density attack. In this paper, we investigate a new Permutation Combination Algorithm. By exploiting this algorithm, we shall propose a novel knapsack public-key cryptosystem. Our proposed scheme can enjoy a high density to avoid the low-density attack. The density \( d \) can also exceed 0.9408 to avoid the low-density attack.

Keywords—Public key, Knapsack problem, Knapsack cryptosystem, low-density attack.

I. INTRODUCTION

In 1976, Diffie and Hellman [6] introduced the public key cryptosystem. In their cryptosystem, two different keys are used: one for encryption and the other for decryption. Each user makes the encryption key public and keeps her/his decryption key secret. Everyone can use the user’s encryption key to send encrypted message to her/him. Then, the user can use his/her decryption key to recover the message. Most public key cryptosystems fall into one of the two categories below [3]:

- Public key cryptosystems based on hard number-theoretic problems: e.g., RSA [2,9,10,16], Rabin [15], and ElGamal [7,8,19] cryptosystems.

Unlike hard number-theoretic problems, the knapsack problem has been proven to be NP-complete [14]. That is to say, there is no polynomial algorithm will be invented to solve the knapsack problem. Breaking hard number-theoretic problems within a reasonable amount of time can be found. Hence, a knapsack cryptosystem is better than those based on hard number-theoretic problems. The knapsack problem is a problem of solving the linear diophantine equation. Let both \( C \) and a set \( A = \{a_1, a_2, \cdots, a_n\} \) be given integers and \( \{x_1, x_2, \cdots, x_n\} \) be unknown variables. The linear diophantine equation is as follows:

\[
C = a_1x_1 + a_2x_2 + \cdots + a_nx_n.
\]

To solve the diophantine equation is to find integer-valued solutions of \( \{x_1, x_2, \cdots, x_n\} \).

A lot of knapsack-type public key cryptosystems have been suggested to be insecure since when the density is low. It becomes weak against the low-density attack [1,4,5,12]. To make sure of the security against the low-density attack, the density must be kept at a high level. In [4], they suggested that the density \( d \) of the knapsack vector must be larger than 0.9408 to avoid low-density attack. Recently, several knapsack cryptosystems with modified low-density attacks [11,18,20,21,22] have been proposed. They tried to take advantage of the exceedingly high speed encryption as well as deciphering operations of the Merkle-Hellman public key cryptosystem. In [20], Su et al. proposed a new knapsack public-key cryptosystem based on elliptic curve discrete logarithm. By appropriately choosing the parameters, one can control the ratio between the number of elements in the elliptic curve cryptography and their size in bits. It has a great effect on completely disguising the vulnerable knapsacks. In [22], Wang et al. proposed a novel probabilistic knapsack-based cryptosystem based on a new easy compact knapsack problem. The proposed scheme enjoyed a high knapsack density and it is secure against low-density attacks. In this paper, we investigate a new Permutation Combination Algorithm. By exploiting this algorithm, we shall propose a novel knapsack public-key cryptosystem. Our proposed scheme can enjoy a high density to avoid the low-density attack. The density \( d \) can also exceed 0.9408 to avoid the low-density attack.

The rest of this paper is organized as follows. We shall propose an algorithm built upon the knapsack problem in the following section. Then, in Section 3, we shall propose our new secure knapsack cryptosystem. The security analysis of the proposed cryptosystem will be discussed in Section 4. Finally, the concluding remarks will be in the last section.

II. PERMUTATION COMBINATION ALGORITHM

In this section, a new algorithm called the Permutation Combination Algorithm is to be proposed. Given a defined original sequence, the Permutation Combination Algorithm can generate a series of permutations developed from the original
sequence. In our new cryptosystem to be proposed in Section 3 later, we will use this algorithm. The algorithm is as follows:

1) Define an original sequence
\[ D_0 = \{E_n, E_{n-1}, \ldots, E_2, E_1\} \]

2) Re-combine all the elements of the original sequence \( D_0 \) which obtain \((n!-1)\) sequences
\[
D_1, D_2, \ldots, D_{n!-1}
\]
\[ n! = n \times (n-1) \times (n-2) \times \cdots \times 2 \times 1. \]

The sequences \( D_i \) \((i = 1, 2, \ldots, n!-1)\) are then defined as follows:

\[
D_0 = \{E_n, E_{n-1}, E_{n-2}, \ldots, E_5, E_4, E_3, E_2, E_1\}
\]
\[ D_1 = \{E_n, E_{n-1}, E_{n-2}, \ldots, E_5, E_4, E_3, E_1, E_2\} \]
\[ D_2 = \{E_n, E_{n-1}, E_{n-2}, \ldots, E_4, E_5, E_3, E_2, E_1\} \]
\[ D_3 = \{E_n, E_{n-1}, E_{n-2}, E_4, E_5, E_3, E_2, E_1\} \]
\[ D_4 = \{E_n, E_{n-1}, E_4, E_5, E_3, E_2, E_1\} \]
\[ D_5 = \{E_n, E_{n-1}, E_4, E_5, E_2, E_1\} \]
\[ \vdots \]
\[ D_{n!-1} = \{E_1, E_2, E_3, \ldots, E_{n-2}, E_{n-1}, E_n\} \]

3) According to the above sequences, each sequence owns a corresponding value called the factorial carry value \( \{F_n, F_{n-1}, F_{n-2}, \ldots, F_5, F_4, F_3, F_2, F_1\} \). Using the factorial carry value, we can efficiently obtain any sequence. The factorial carry value is defined as follows:

\[
\{F_n, F_{n-1}, F_{n-2}, \ldots, F_5, F_4, F_3, F_2, F_1\}
\]
\[ \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \uparrow \]
\[ (n-1)! (n-2)! (n-3)! \cdots 4! 3! 2! 1! 0 \]

For instance, suppose we want to get the sequence \( D_6 \). We can compute the factorial carry value \( \{F_n, F_{n-1}, F_{n-2}, \ldots, F_5, F_4, F_3, F_2, F_1\} \) of \( D_6 \) as:

\[ 6 = 0 \times (n-1)! + 0 \times (n-2)! + 0 \times (n-3)! + \cdots + 0 \times 4! + 1 \times 3! + 0 \times 2! + 0 \times 1! + 0 \]

So, the factorial carry value of \( D_6 \) is \( \{0, 0, 0, \ldots, 1, 0, 0, 0\} \).

4) With the knowledge of the original sequence \( D_0 = \{E_n, E_{n-1}, E_{n-2}, \ldots, E_5, E_4, E_3, E_2, E_1\} \) and the factorial carry value \( \{0, 0, 0, \ldots, 1, 0, 0, 0\} \) of \( D_6 \), we can compute sequence \( D_6 \) as follows:

Get \( E_n \) by introducing \( F_n = 0 \). Here, the remaining elements in the sequence are \( \{E_{n-1}, E_{n-2}, \ldots, E_5, E_4, E_3, E_2, E_1\} \).

Get \( E_{n-1} \) by introducing \( F_{n-1} = 0 \). Here, the remaining elements in the sequence are \( \{E_{n-2}, \ldots, E_5, E_4, E_3, E_2, E_1\} \).

Get \( E_{n-2} \) by introducing \( F_{n-2} = 0 \). Here, the remaining elements in the sequence are \( \{E_{n-3}, \ldots, E_5, E_4, E_3, E_2, E_1\} \).

\vdots

Get \( E_5 \) by introducing \( F_5 = 0 \). Here, the remaining elements in the sequence are \( \{E_4, E_3, E_2, E_1\} \).

Get \( E_4 \) by introducing \( F_4 = 1 \). Here, the remaining elements in the sequence are \( \{E_3, E_2, E_1\} \).

Get \( E_3 \) by introducing \( F_3 = 0 \). Here, the remaining elements in the sequence are \( \{E_2, E_1\} \).

Get \( E_2 \) by introducing \( F_2 = 0 \). Here, the remaining element is \( \{E_1\} \).

Get \( E_1 \) by introducing \( F_1 = 0 \). Therefore, the sequence \( D_6 = \{E_n, E_{n-1}, E_{n-2}, \ldots, E_5, E_4, E_3, E_2, E_1\} \).

In accordance with the above algorithm, let’s take sequence \( D_{100} \) for example as follows:

1) Generate the original sequence \( D_0 \) as
\[ D_0 = \{A, B, C, D, E, F\} \]

2) Compute the factorial carry value of \( D_{100} \)
\[ 100 = 0 \times 5! + 4 \times 4! + 0 \times 3! + 2 \times 2! + 0 \times 1! + 0 \]

Then, the factorial carry value of \( D_{100} \) is \( \{0, 4, 0, 2, 0, 0\} \).

3) Compute sequence \( D_{100} \) with its factorial carry value \( \{0, 4, 0, 2, 0, 0\} \).

\begin{align*}
0 & \rightarrow \{A, B, C, D, E, F\} \rightarrow A \\
4 & \rightarrow \{B, C, D, E, F\} \rightarrow F \\
0 & \rightarrow \{B, C, D, E\} \rightarrow B \\
2 & \rightarrow \{C, D, E\} \rightarrow E \\
0 & \rightarrow \{C, D\} \rightarrow C \\
0 & \rightarrow \{D\} \rightarrow D
\end{align*}

The permutation of sequence \( D_{100} \) is \( \{A, F, B, E, C, D\} \).
III. THE PROPOSED KNAPSACK CRYPTOSYSTEM

In this section, a new secure knapsack cryptosystem based on the Merkle-Hellman public-key cryptosystem will be proposed. A message $M$ will be encrypted the ciphertext and signed the digital signature. Then, the sender sends the ciphertext and the digital signature to the verifier. The verifier can also represent to decrypt the ciphertext and authenticate the signature. The procedure of the proposed cryptosystem contains four phases: the encryption phase, the decryption phase, the signature generation phase, and the signature verification phase. In the initial stage, each user chooses a super increasing sequence $B = \{b_1, b_2, \cdots, b_{360}\}$ as secret key vector.

Each user transfers super increasing sequence $A = \{a_1, a_2, \cdots, a_{1360}\}$ as public key vector. $W$ and $W'$ are secret modular multipliers, relatively prime to $P$.

$$\begin{align*}
    W &> \sum_{j=1}^{1360} b_j, \\
gcd(W, P) & = 1, \\
W \times W' & \equiv 1 \text{ mod } P.
\end{align*}$$

Further, each user chooses a random $170 \times 256$ binary matrix $H$, a vector $R = (r_1, r_2, \cdots, r_{256})^T$ and a vector $HR = (hr_1, hr_2, \cdots, hr_{170})^T$ to satisfy the following equation:

$$H \cdot R = HR \text{ mod } n$$

$$= \begin{pmatrix} h_{1,1} & \cdots & h_{1,256} \\ \vdots & \ddots & \vdots \\ h_{170,1} & \cdots & h_{170,256} \end{pmatrix} \begin{pmatrix} r_1 \\ \vdots \\ r_{256} \end{pmatrix} = \begin{pmatrix} hr_1 \\ \vdots \\ hr_{170} \end{pmatrix}$$

$$= 2^9 \mod n$$

Let $H(\cdot)$ be a one-way hash function. The proposed scheme involves two parties: the sender and the verifier. Let $A$ be a sender and $B$ be a verifier. Then, $A$ and $B$’s secret and public parameters are listed in Table 1.

A. Encryption Phase

The sender $A$ executes the following steps to generate the ciphertext $C$ of the message $M$.

1) Compute the digest $D$ of $M$ as $D = H_{1024}(M)$.

Let $D$ denotes a 1024-bit message.

2) Generate $D'$ from $D$. The method is as follows:

a) $D$ has 1024 bits, which means there can be approximately $1.7 \times 10^{308}$ variations of $D$.

b) Compute $170!$, which approximates $10^{106}$.

c) $D'$ is derived as follows:

$$D' = D \text{ mod } 170!.$$ Here, $D'$ is smaller than the integer $170!$.

3) Compute the factorial carry value $U = \{u_1, u_2, \cdots, u_{170}\}$ of $D'$.

$$D' = u_1 \times 169! + u_2 \times 168! + \cdots + u_{169} \times 1! + u_{170} \times 0$$

4) Divide $B$’s public key vector $A_b = \{a_{b1}, a_{b2}, \cdots, a_{b1360}\}$ into 8 subset public key vectors. Each subset public key vector has 170 elements.

$$A_b = \{a_{b1}, a_{b2}, \cdots, a_{b170} \},$$

$$\{a_{b171}, a_{b172}, \cdots, a_{b340} \},$$

$$\{a_{b341}, a_{b342}, \cdots, a_{b510} \},$$

$$\{a_{b511}, a_{b512}, \cdots, a_{b680} \},$$

$$\{a_{b681}, a_{b682}, \cdots, a_{b850} \},$$

$$\{a_{b851}, a_{b852}, \cdots, a_{b1020} \},$$

$$\{a_{b1021}, a_{b1022}, \cdots, a_{b1360} \}$$

$$5) \text{ Recombine each subset public key vector using }$$

$$U = \{u_1, u_2, \cdots, u_{170}\} \text{ by means of the Permutation Combination Algorithm. } A \text{ chooses each subset public key vector in the first 128 elements. Then, } A \text{ will obtain 1024 elements } A_{au} = \{au_{b1}, au_{b2}, \cdots, au_{b1024}\}.$$  

6) $M$ is divided into $\{M_1, M_2, \cdots, M_j\}$. Each $M_k$ is a 1024-bit message ($k = 1, 2, \cdots, j$).

$$M_k = \{x_{k1}, x_{k2}, \cdots, x_{k1024} \}$$
\[ M_2 = \{x_{2,1}, x_{2,2}, \ldots, x_{2,1024}\} \]
\[
\vdots \]
\[ M_j = \{x_{j,1}, x_{j,2}, \ldots, x_{j,1024}\} \]

7) The corresponding ciphertext \( C_k \) is given as the product of \( A_{bu} \) and \( M_k \) \((k = 1, 2, \ldots, j)\).
\[
C_1 = \sum_{i=1}^{1024} au_{b_i} \times x_{1,i}
\]
\[
C_2 = \sum_{i=1}^{1024} au_{b_i} \times x_{2,i}
\]
\[
\vdots
\]
\[
C_j = \sum_{i=1}^{1024} au_{b_i} \times x_{j,i}
\]

Then, the set of the ciphertext \( \{C_1, C_2, \ldots, C_j\} \) is a ciphertext \( C \). A sends \( C \) and \( D' \) to \( B \) through the insecure channel.

B. Decryption Phase

After receiving \( C \) and \( D' \), \( B \) executes the following steps to derive \( M \) from \( C \) and \( D' \).

1) Compute the factorial carry value
\[
U = \{u_1, u_2, \ldots, u_{170}\} \text{ of } D'.
\]
\[
D' = u_1 \times 169! + u_2 \times 168! + \cdots + u_{169} \times 1! + u_{170} \times 0
\]

2) Divide \( B \)'s secret key vector
\[
B = \{b_{b_1}, b_{b_2}, \ldots, b_{b_{1024}}\} \text{ into 8 subset public key vectors. Then, each subset secret key vector has 170 elements.}
\]
\[
B_b = \{(b_{b_1}, b_{b_2}, \ldots, b_{b_{340}}),
\]
\[
(b_{b_{341}}, b_{b_{342}}, \ldots, b_{b_{510}}),
\]
\[
(b_{b_{511}}, b_{b_{512}}, \ldots, b_{b_{680}}),
\]
\[
(b_{b_{681}}, b_{b_{682}}, \ldots, b_{b_{850}}),
\]
\[
(b_{b_{851}}, b_{b_{852}}, \ldots, b_{b_{1020}}),
\]
\[
(b_{b_{1021}}, b_{b_{1022}}, \ldots, b_{b_{1190}}),
\]
\[
(b_{b_{1191}}, b_{b_{1192}}, \ldots, b_{b_{1360}})\}
\]

3) Recombine each subset secret key vector using
\[
U = \{u_1, u_2, \ldots, u_{170}\} \text{ by means of the Permutation Combination Algorithm.} \]
\( B \) chooses each subset secret key vector in the first 128 elements. Then, \( B \) will obtain 1024 elements \( B_{bu} = \{bu_{b_1}, bu_{b_2}, \ldots, bu_{b_{1024}}\} \).

However, \( B_{bu} = \{bu_{b_1}, bu_{b_2}, \ldots, bu_{b_{1024}}\} \) is still a super increasing sequence. In other words, the elements of \( B_{bu} \) do not change order.

4) Divide \( C \) into \( \{C_1, C_2, \ldots, C_j\} \). Each \( C_k \) is a 1024-bit ciphertext \((k = 1, 2, \ldots, j)\).

5) Compute the recombine message \( Mre_k \), which is given as the product of \( C_k \) and \( W' \) \((k = 1, 2, \ldots, j)\).
\[
Mre_k = C_k \times W' \text{ mod } P
\]
\[
= \sum_{i=1}^{1024} (au_{b_i} \times x_{k,i}) \times W' \text{ mod } P
\]
\[
= \sum_{i=1}^{1024} (bu_{b_i} \times W \times x_{k,i}) \times W' \text{ mod } P
\]
\[
= \sum_{i=1}^{1024} bu_{b_i} \times x_{k,i} \text{ mod } P
\]

6) The message \( \{M_1, M_2, \ldots, M_j\} \) is then obtained through recombining each pre-recombining message \( \{Mre_1, Mre_2, \ldots, Mre_j\} \) by using
\[
U = \{u_1, u_2, \ldots, u_{170}\} \text{ through the Permutation Combination Algorithm.}
\]

Then, the set of \( \{M_1, M_2, \ldots, M_j\} \) is the real message \( M \).

C. Signature Generation Phase

Without loss of generality, \( A \) executes the following steps to sign a signature from \( M \).

1) Divide binary matrix \( H_a \) into 256 subset vectors. Each subset vector has 170 elements.
\[
H_a = [(h_{1,1}, h_{1,2}, \ldots, h_{1,170})^T,
\]
\[
(h_{1,2}, h_{2,2}, \ldots, h_{2,170})^T,
\]
\[
\vdots
\]
\[
(h_{1,256}, h_{2,256}, \ldots, h_{256,256})^T]
\]

2) Recombine the binary matrix \( H_a \) using
\[
U = \{u_1, u_2, \ldots, u_{170}\} \text{ by means of the Permutation Combination Algorithm.} \]
\( A \) chooses each subset vector in the first 128 elements. Then, \( A \) will obtain \( 128 \times 256 \)-binary matrix \( H_a \).
\[
H_a = \begin{bmatrix}
h'_{1,1} & \cdots & h'_{1,256} \\
\vdots & \ddots & \vdots \\
h'_{128,1} & \cdots & h'_{128,256}
\end{bmatrix}
\]

3) Compute the digest \( D_M \) of \( D \) as
\[
D_M = H_{128}(D).
\]
Let \( D_M \) be a 128-bit message.
4) Generate inverse binary sequence
\[ D'_M = (m_1, m_2, \ldots, m_{2^{128}}) \] from \( D_M \). I.e., if
\[ D_M = (011)_2 \text{ then } D'_M = (110)_2. \]
5) Compute a signature \( S = (s_1, s_2, \ldots, s_{256}) \) as
\[
S = D'_M H'_d = \begin{pmatrix}
    h'_{1.1} & \cdots & h'_{1.256} \\
    \vdots & \ddots & \vdots \\
    h'_{128.1} & \cdots & h'_{128.256}
\end{pmatrix}
\]
\[ s_j = \sum_{i=1}^{2^{128}} m_i h'_{i,j} \quad j = 1, 2, \ldots, 256 \]
A sends the digital signature \( S \) to \( B \) through the insecure channel.

D. Signature Verification Phase

\( B \) executes the following steps to verify the validity of signature \( S \).

1) Use \( A \)'s public key \( R_a \) to compute the pre-recombine message \( \text{Mre} \) which is given as the product of \( S \) and \( R_a \).

\[
\text{Mre} = S \cdot R_a \mod n
\]
\[ = \sum_{j=1}^{2^{256}} s_j \cdot r_j \mod n
\]
\[ = \sum_{j=1}^{2^{256}} \left( \sum_{i=1}^{2^{128}} m_i \cdot h'_{i,j} \right) r_j \mod n
\]
\[ = \sum_{j=1}^{2^{128}} \left( \sum_{i=1}^{2^{256}} h'_{i,j} \cdot r_j \right) m_i \mod n
\]
\[ = \sum_{j=1}^{2^{128}} h'_{i,j} \cdot r_j \mod n
\]
2) Recombine the message \( \text{Mre} \) to obtain \( D_M \) using
\( U = \{u_1, u_2, \ldots, u_{2^{128}}\} \) by means of the Permutation Combination Algorithm. Then, \( B \) can check the validity of \( S \) of \( M \) through the following equation:
\[ D_M = H_{128}(H_{1024}(M)) \]
If the equation holds, the message \( M \) is authenticated and the digital signature \( S \) is valid.

IV. SECURITY ANALYSIS

The security of the proposed cryptosystem is based on the cryptographic assumption of the intractability of the knapsack problem. Most knapsack cryptosystems can be easily broken by the famous low-density attack proposed by Lagarias and Odlyzko [12].

We now discuss the range of \( P \). Suppose \( Q = \{b_1, b_2, \ldots, b_n\} = \{2^0, 2^1, \ldots, 2^{n-1}\} \). We can obtain
\[
\sum_{i=0}^{j-1} 2^i = 2^j - 1,
\]
\[ 2^j > \sum_{i=0}^{j-1} 2^i. \]
\( Q \) is a super increasing sequence and \( \sum_{i=0}^{n} b_i = 2^n - 1 \). In order to make \( P \) satisfy the proposed cryptosystem, \( P \) must be larger than \( 2^n \). When \( n = 1360 \), \( P \geq 2^{1360} = 2.5164 \times 10^{1009} \).

The density of knapsack cryptosystem is defined as
\[ d = \frac{n}{\log_2(\max(b_i))} \quad (1 \leq i \leq n). \]
When the density \( d \) is smaller than 0.9408, the knapsack public key cryptosystem becomes vulnerable to the low-density attack [4]. So, the density \( d' \) must be kept larger than 0.9408 to make the proposed cryptosystem stay secure. Let \( A_b \) be \( \{a_{b1}, a_{b2}, \ldots, a_{b1360}\} \), and then the range of \( P \) is:
\[ 0.9408 \leq \frac{n}{\log_2(P) - 1} \leq 1.4534 \times 10^{435} \]
\[ \log_2(P - 1) \leq 1445.5782 \ldots \]
\[ P - 1 \leq 2^{1445.5782} \ldots + 1 \]
\[ P \leq 1.4534 \times 10^{435} \]
According to the above statement, the range of \( P \) of our cryptosystem is \( (2.5164 \times 10^{409}, 1.4534 \times 10^{435}) \). Observing the definition of density, we come to two ways of increasing the density: increasing \( n \) and decreasing \( \log_2(\max(b_i)) \). According to the above discussion, we define the range of \( P \) to be \( (2.5164 \times 10^{409}, 1.4534 \times 10^{435}) \). In other words, the density of the proposed cryptosystem did exceed 0.9408 to avoid the low-density attack.

V. CONCLUSIONS

In this paper, a new knapsack cryptosystem based on permutation combination algorithm has been proposed. The proposed cryptosystem stays away from the low-density attack by keeping the density high.

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Min-Shiang Hwang was born on August 27, 1960 in Tainan, Taiwan, Republic of China (ROC). He received the B.S. in Electronic Engineering from National Chiao Tung University, Taichung, Taiwan, ROC, in 1980; and the M.S. in Industrial Engineering from National Tsing Hua University, in 1988; and the Ph.D. in Computer and Information Science from National Chiao Tung University, Taiwan, in 1995. He also studied Applied Mathematics at National Cheng Kung University, Taiwan, from 1984-1986. Dr. Hwang passed the National Higher Examination in field “Electronic Engineer” in 1988. He also passed the National Telecommunication Special Examination in field “Information Engineering”, qualified as advanced technician the first class in 1990.

From 1988 to 1991, he was the leader of the Computer Center at Telecommunication Laboratories (TL), Ministry of Transportation and Communications, ROC. He was also a chairman of the Department of Information Management, Chaoyang University of Technology (CYUT), Taiwan, during 1999-2002. He was a professor and chairman of the Graduate Institute of Networking and Communications, CYUT, during 2002-2003. He is currently a professor of the department of Management Information System, National Chung Hsing University, Taiwan, ROC.


Cheng-Chi Lee received the B.S. and M.S. in Information Management from Chaoyang University of Technology (CYUT), Taichung, Taiwan, in 1999 and in 2001. He researched in Computer and Information Science from National Chiao Tung University (NCTU), Taiwan, Republic of China, from 2001 to 2003. He received the Ph.D. in Computer Science from National Chung Hsing University (NCHU), Taiwan, in 2007. He was a Lecturer of Computer and Communication, Asia University, from 2004 to 2007. From 2007, he is an assistant professor of Computer and Communication, Asia University. His current research interests include information security, cryptography, and mobile communications.

Shiang-Feng Tseng received the B.S. and M.S. in Information Management from Chaoyang University of Technology (CYUT), Taichung, Taiwan, in 2001 and in 2003. His current research interests include information security, cryptography, and mobile communications.