Cryptography and Network Security

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Chapter 8

Encipherment Using Modern Symmetric-Key Ciphers

Chapter 18
Objectives

- To show how modern standard ciphers, such as DES or AES, can be used to encipher long messages.
- To discuss five modes of operation designed to be used with modern block ciphers.
- To define which mode of operation creates stream ciphers out of the underlying block ciphers.
- To discuss the security issues and the error propagation of different modes of operation.
- To discuss two stream ciphers used for real-time processing of data.

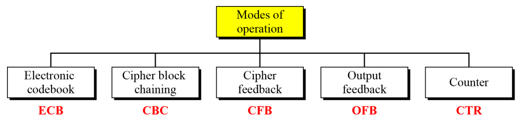
8-1 USE OF MODERN BLOCK CIPHERS

Symmetric-key encipherment can be done using modern block ciphers. Modes of operation have been devised to encipher text of any size employing either DES or AES.

Topics discussed in this section:

8-1 Continued

Figure 8.1 *Modes of operation*



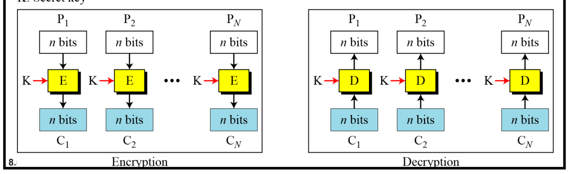
8.1.1 Electronic Codebook (ECB) Mode

The simplest mode of operation is called the electronic codebook (ECB) mode.

Encryption: $C_i = E_K(P_i)$ Decryption: $P_i = D_K(C_i)$

Figure 8.2 *Electronic codebook (ECB) mode*

E: Encryption D: Decryption
P_i: Plaintext block i C_i: Ciphertext block i
K: Secret key



8.1.1 Continued

Example 8.1

It can be proved that each plaintext block at Alice's site is exactly recovered at Bob's site. Because encryption and decryption are inverses of each other,

Encryption: $C_i = E_K(P_i)$ Decryption: $P_i = D_K(C_i)$

Example 8.2

This mode is called electronic codebook because one can precompile 2^K codebooks (one for each key) in which each codebook has 2^n entries in two columns. Each entry can list the plaintext and the corresponding ciphertext blocks. However, if K and n are large, the codebook would be far too large to precompile and maintain.

8.1.1 Continued

Example 8.3

Assume that Eve works in a company a few hours per month (her monthly payment is very low). She knows that the company uses several blocks of information for each employee in which the seventh block is the amount of money to be deposited in the employee's account. Eve can intercept the ciphertext sent to the bank at the end of the month, replace the block with the information about her payment with a copy of the block with the information about the payment of a full-time colleague. Each month Eve can receive more money than she deserves.

8.7

8.1.1 Continued

Error Propagation

A single bit error in transmission can create errors in several in the corresponding block. However, the error does not have any effect on the other blocks.

Algorithm 8.1 *Encryption for ECB mode*

```
ECB_Encryption (K, Plaintext blocks)
{
    for (i = 1 to N)
    {
        C_i ← E_K (P_i)
    }
    return Ciphertext blocks
}
```

8.8

8.1.1 Continued

Ciphertext Stealing

A technique called ciphertext stealing (CTS) can make it possible to use ECB mode without padding. In this technique the last two plaintext blocks, P_{N-1} and P_N, are encrypted differently and out of order, as shown below, assuming that P_{N-1} has n bits and P_N has m bits, where m $\leq$ n .

$$X = E_K(P_{N-1}) \rightarrow C_N = head_m(X)$$
$$Y = P_N \mid tail_{n-m}(X) \rightarrow C_{N-1} = E_K(Y)$$

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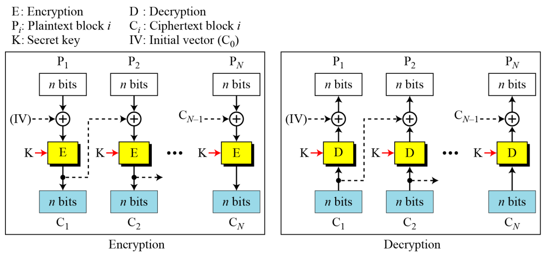
8.1.2 Cipher Block Chaining (CBC) Mode

In CBC mode, each plaintext block is exclusive-ored with the previous ciphertext block before being encrypted.

Figure 8.3 *Cipher block chaining (CBC) mode*



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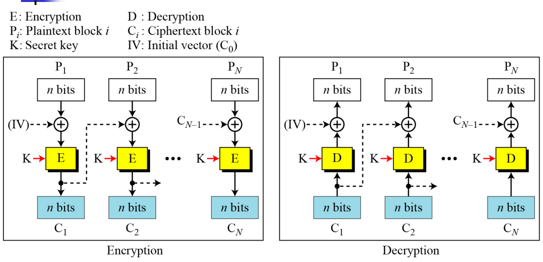
8.1.2 Continued

Figure 8.3 *Cipher block chaining (CBC) mode*



Encryption:	Decryption:
$C_0 = IV$	$C_0 = IV$
$C_i = E_K(P_i \oplus C_{i-1})$	$P_i = D_K(C_i) \oplus C_{i-1}$

8.11

8.1.2 Continued

Example 8.4

It can be proved that each plaintext block at Alice's site is recovered exactly at Bob's site. Because encryption and decryption are inverses of each other,

$$P_i = D_K(C_i) \oplus C_{i-1} = D_K(E_K(P_i \oplus C_{i-1})) \oplus C_{i-1} = P_i \oplus C_{i-1} \oplus C_{i-1} = P_i$$

Initialization Vector (IV)

The initialization vector (IV) should be known by the sender and the receiver.

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8.1.2 Continued

Error Propagation

In CBC mode, a single bit error in ciphertext block C_j during transmission may create error in most bits in plaintext block P_j during decryption.

Algorithm 8.2 *Encryption algorithm for ECB mode*

```
CBC_Encryption (IV, K, Plaintext blocks)
{
    C0 ← IV
    for (i = 1 to N)
    {
        Temp ← Pi ⊕ Ci−1
        Ci ← EK (Temp)
    }
    return Ciphertext blocks
}
```


8.1.2 Continued

Ciphertext Stealing

The ciphertext stealing technique described for ECB mode can also be applied to CBC mode, as shown below.

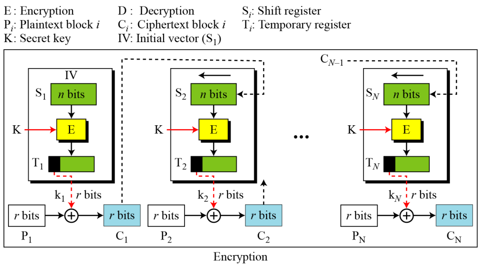
$$U = P_{N-1} \oplus C_{N-2} \quad \rightarrow \quad X = E_K(U) \quad \rightarrow \quad C_N = head_m(X)$$
$$V = P_N \mid pad_{n-m}(0) \quad \rightarrow \quad Y = X \oplus V \quad \rightarrow \quad C_{N-1} = E_K(Y)$$

The head function is the same as described in ECB mode; the pad function inserts 0's.

8.1.3 Cipher Feedback (CFB) Mode

In some situations, we need to use DES or AES as secure ciphers, but the plaintext or ciphertext block sizes are to be smaller.

Figure 8.4 ***Encryption in cipher feedback (CFB) mode***



8.1.3 Continued

Note

In CFB mode, encipherment and decipherment use the encryption function of the underlying block cipher.

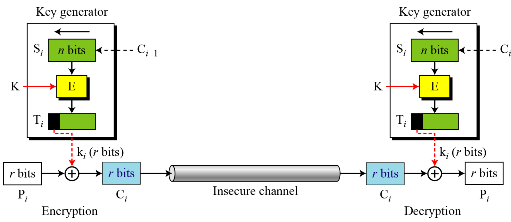
The relation between plaintext and ciphertext blocks is shown below:

Encryption: $C_i = P_i \oplus \text{SelectLeft}_r\{E_K[\text{ShiftLeft}_r(S_{i-1}) \mid C_{i-1})]\}$
Decryption: $P_i = C_i \oplus \text{SelectLeft}_r\{E_K[\text{ShiftLeft}_r(S_{i-1}) \mid C_{i-1})]\}$

8.1.3 Continued

CFB as a Stream Cipher

Figure 8.5 ***Cipher feedback (CFB) mode as a stream cipher***



8.1.3 Continued

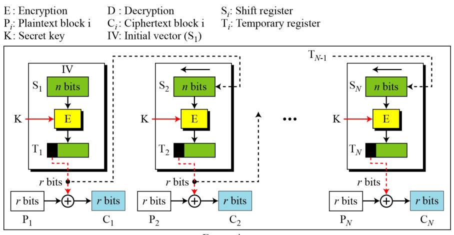
Algorithm 8.3 *Encryption algorithm for CFB*

```
CFB_Encryption (IV, K, r)
{
   i ← 1
   while (more blocks to encrypt)
   {
   input (Pi)
   if (i = 1)
     S ← IV
   else
     {
     Temp ← shiftLeftr (S)
     S ← concatenate (Temp, Ci−1)
     }
   T ← EK(S)
   ki ← selectLeftr (T)
   Ci ← Pi ⊕ ki
   output (Ci)
   i ← i + 1
   }
}
```

18.1.4 Output Feedback (OFB) Mode

In this mode each bit in the ciphertext is independent of the previous bit or bits. This avoids error propagation.

Figure 8.6 *Encryption in output feedback (OFB) mode*



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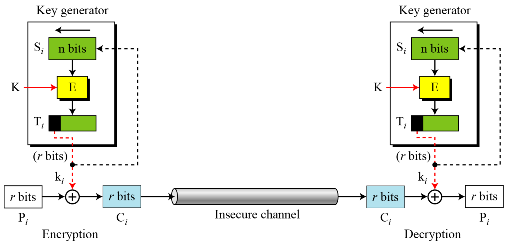
8.1.4 Continued

OFB as a Stream Cipher

Figure 8.7 *Output feedback (OFB) mode as a stream cipher*



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8.1.4 Continued

Algorithm 8.4 *Encryption algorithm for OFB*

```
OFB_Encryption (IV, K, r)
{
    i ← 1
    while (more blocks to encrypt)
    {
        input (P_i)
        if (i = 1)  S ← IV
        else
        {
            Temp ← shiftLeft_r (S)
            S  ← concatenate (Temp, k_{i-1})
        }
        T ← E_K (S)
        k_i ← selectLeft_r (T)
        C_i ← P_i ⊕ k_i
        output (C_i)
        i ← i + 1
    }
}
```

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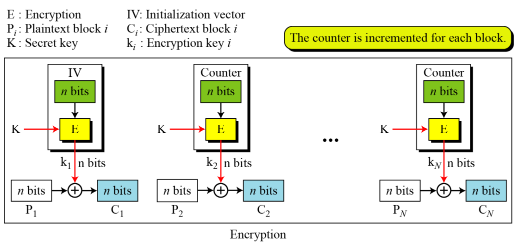
8.1.5 Counter (CTR) Mode

In the counter (CTR) mode, there is no feedback. The pseudorandomness in the key stream is achieved using a counter.

Figure 8.8 *Encryption in counter (CTR) mode*



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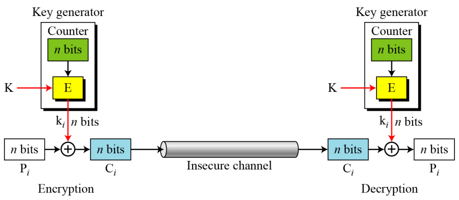
8.1.5 Continued

Figure 8.9 *Counter (CTR) mode as a stream cipher*



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8.1.5 Continued

Algorithm 8.5 *Encryption algorithm for CTR*

```
CTR_Encryption (IV, K, Plaintext blocks)
{
    Counter ← IV
    for (i = 1 to N)
    {
        Counter ← (Counter + i − 1) mod 2^N
        k_i ← E_K (Counter)
        C_i ← P_i ⊕ k_i
    }
    return Ciphertext blocks
}
```

8.24