Chapter 4

Channel Coding and Error Control

Adapted from class notes by
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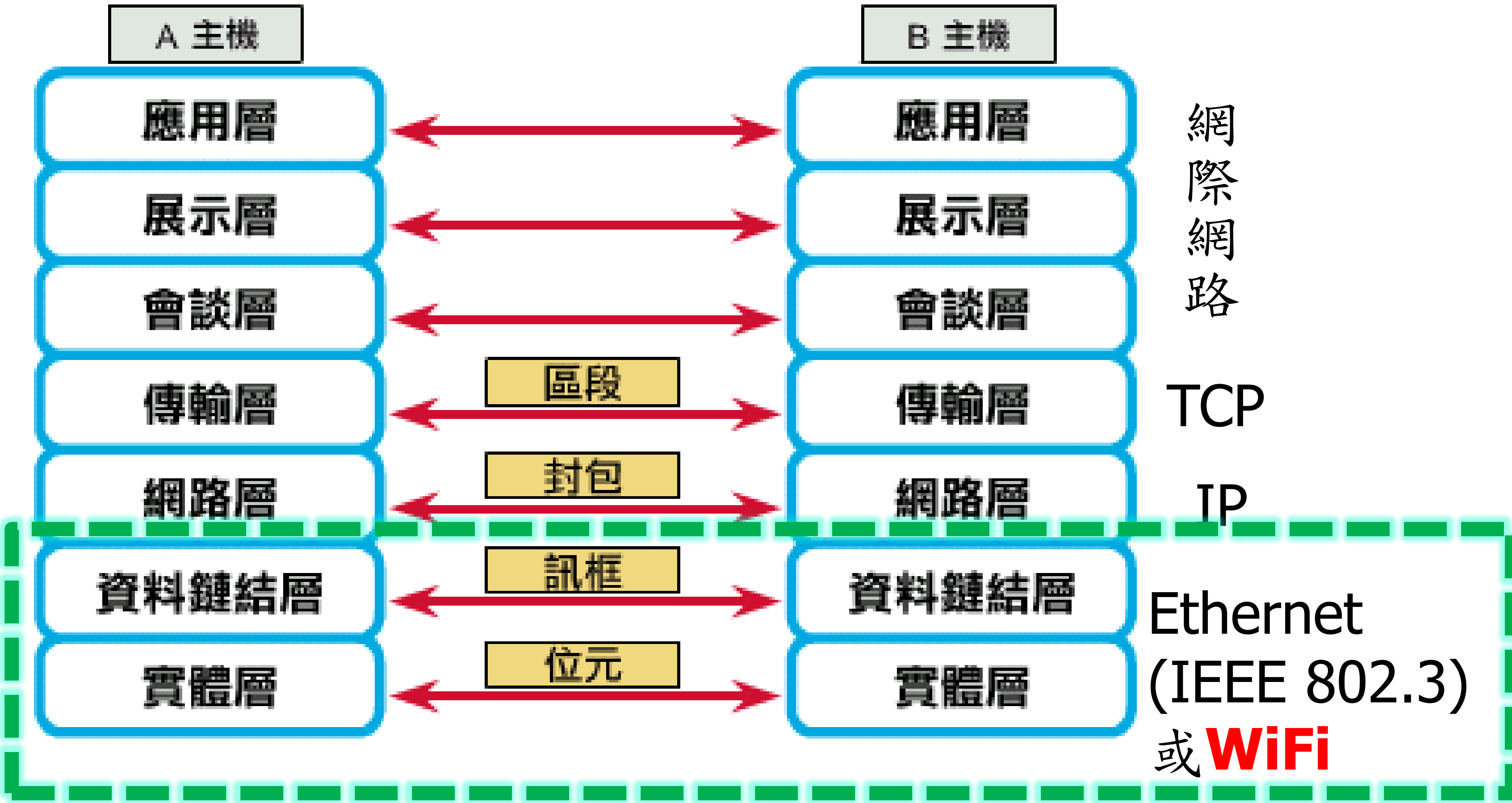
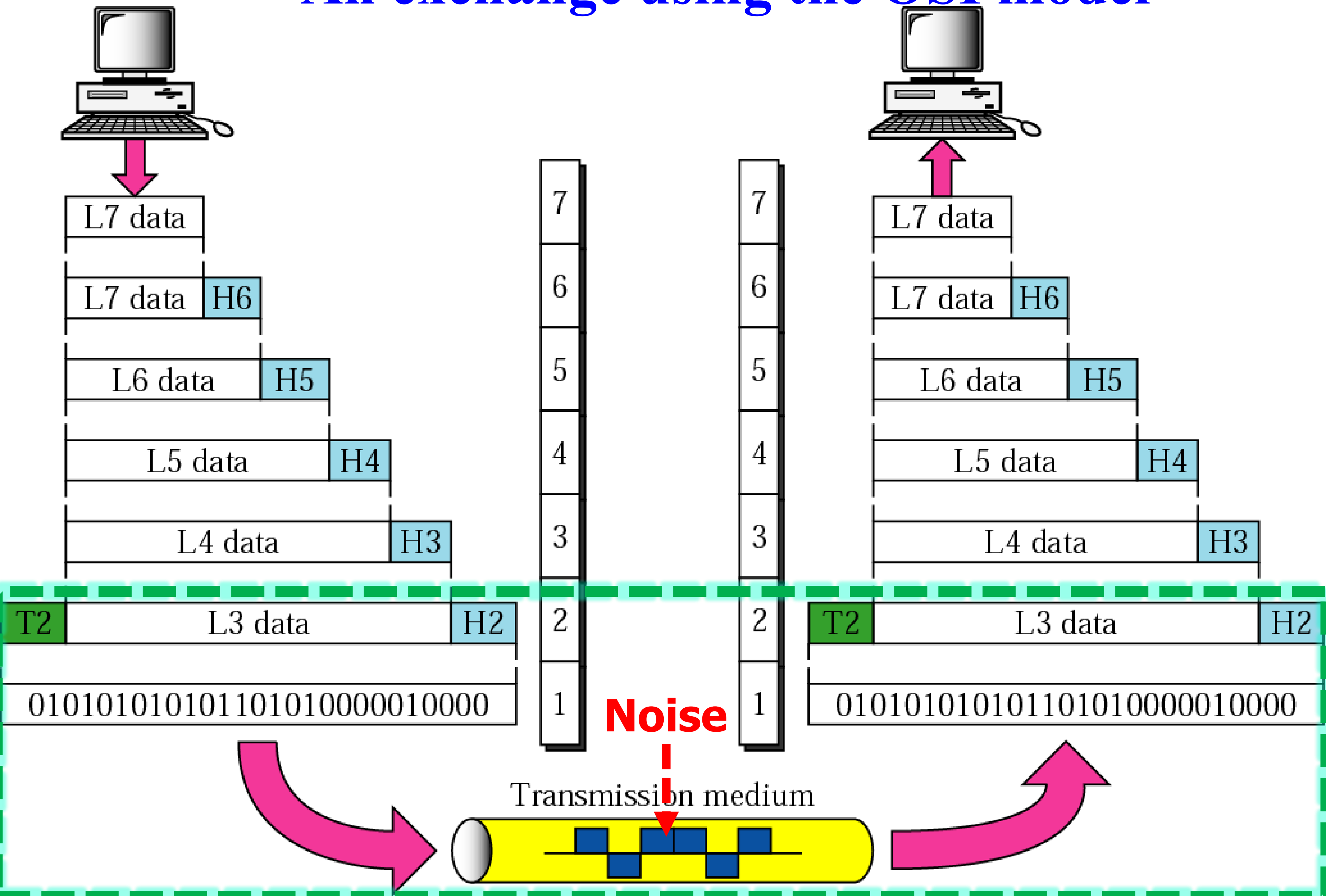
Most slides based on publisher's slides for 1st and 2nd edition of:
Introduction to Wireless and Mobile Systems by Agrawal & Zeng

Protocol Hierarchies (cont.)

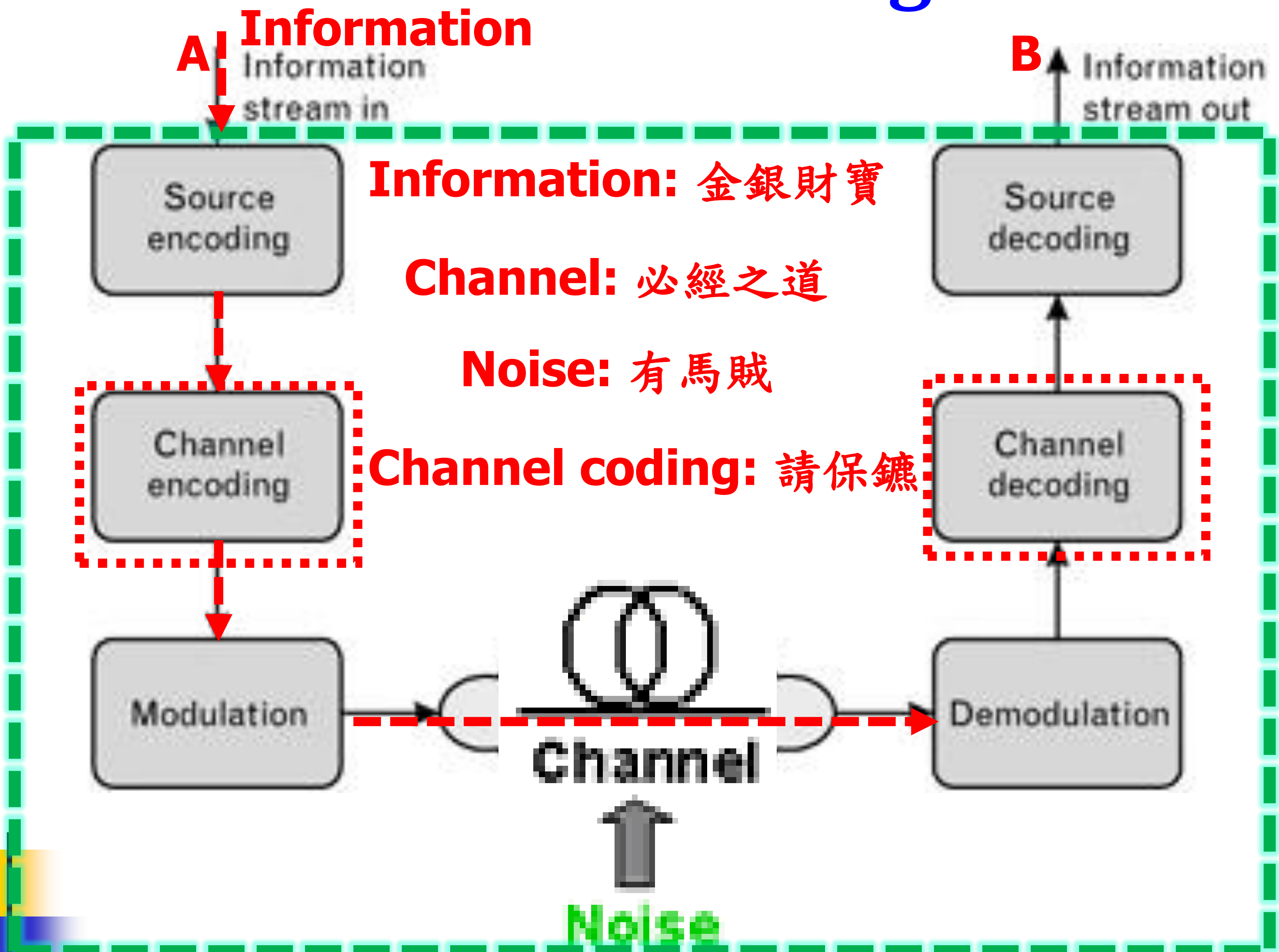
- 對等式通訊(Peer-to-Peer)



An exchange using the OSI model



Channel/ Channel coding



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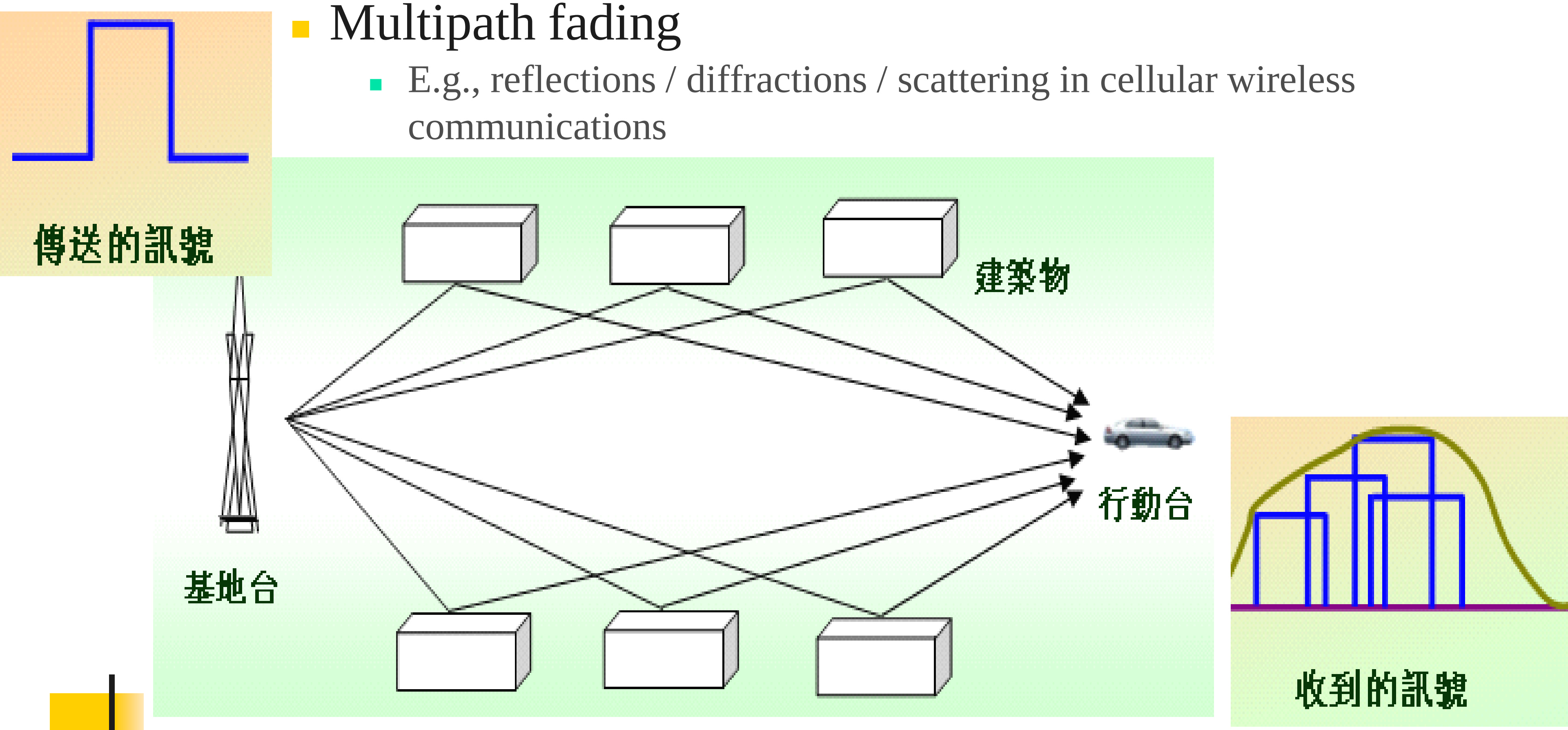
4.1. Introduction

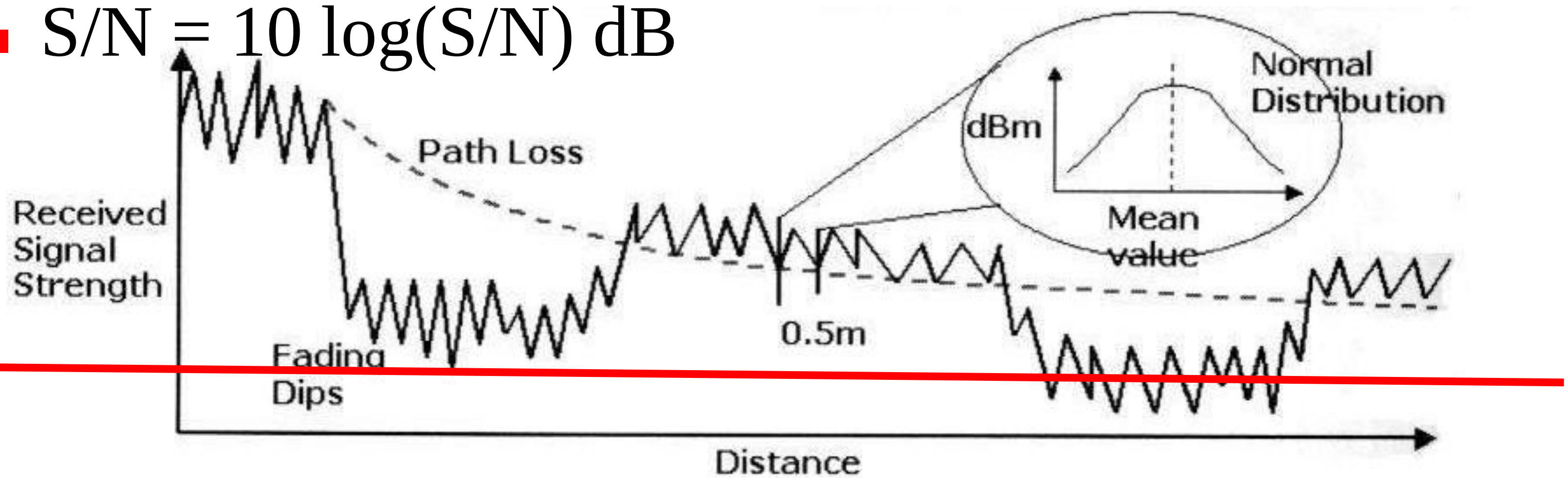
- Why need **channel coding** for radio communication?
  - Severe transmission problems
    - In **terrestrial mobile** communications due to:
      - Multipath fading
        - E.g., reflections / diffractions / scattering in cellular wireless communications



➔ Low S/N (signal-to-noise) ratio = SNR

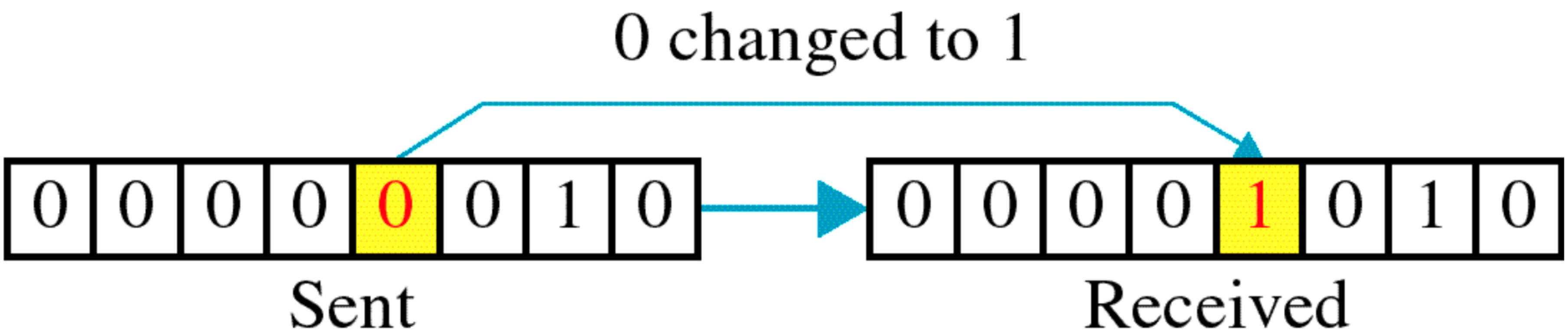
S/N Ratio (SNR), SIR

- 訊號與雜訊比(Signal to Noise Ratio; Signal to Interference Ratio)
- 雜訊(Noise)對訊號(Signal)的干擾程度
  - S/N或S/I: 通常以dB來表示比值
  - S/N值愈高，訊號品質愈好
  - 必須使S/N > 1 (其dB值>0)
  - 提高發射功率，可使S/N值提高，但須規範
  - S/N = 10 log(S/N) dB

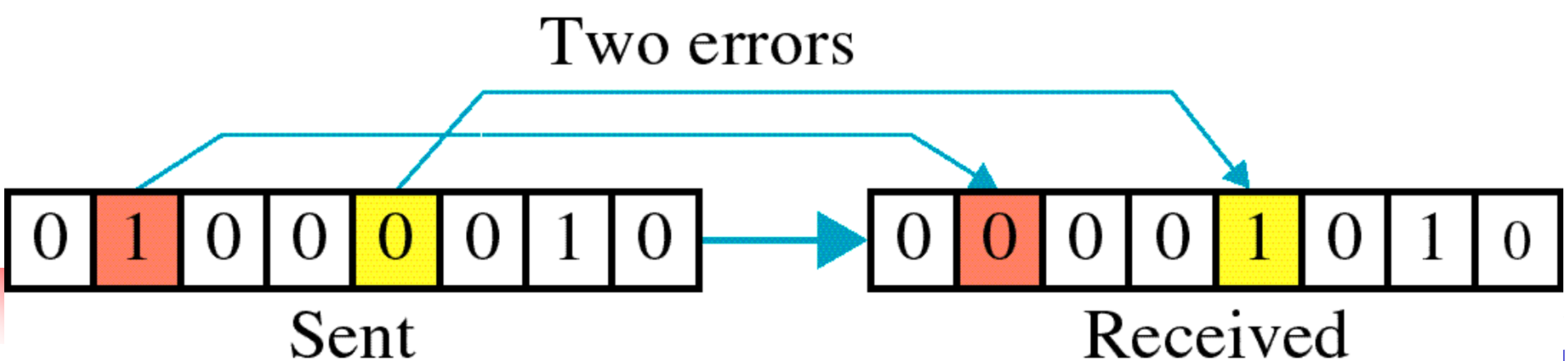


Error Control Process (1)

Single-bit error

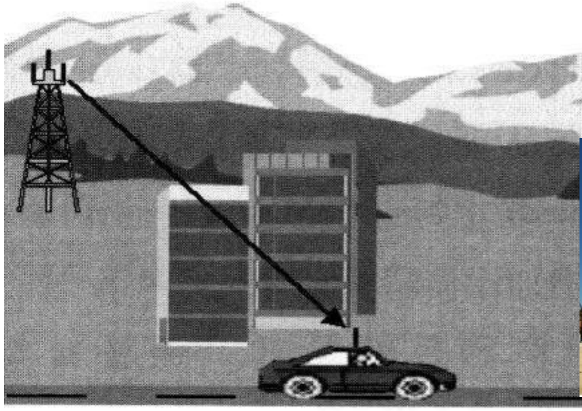


Multiple-bit error



Error Control Process (2)

Burst error



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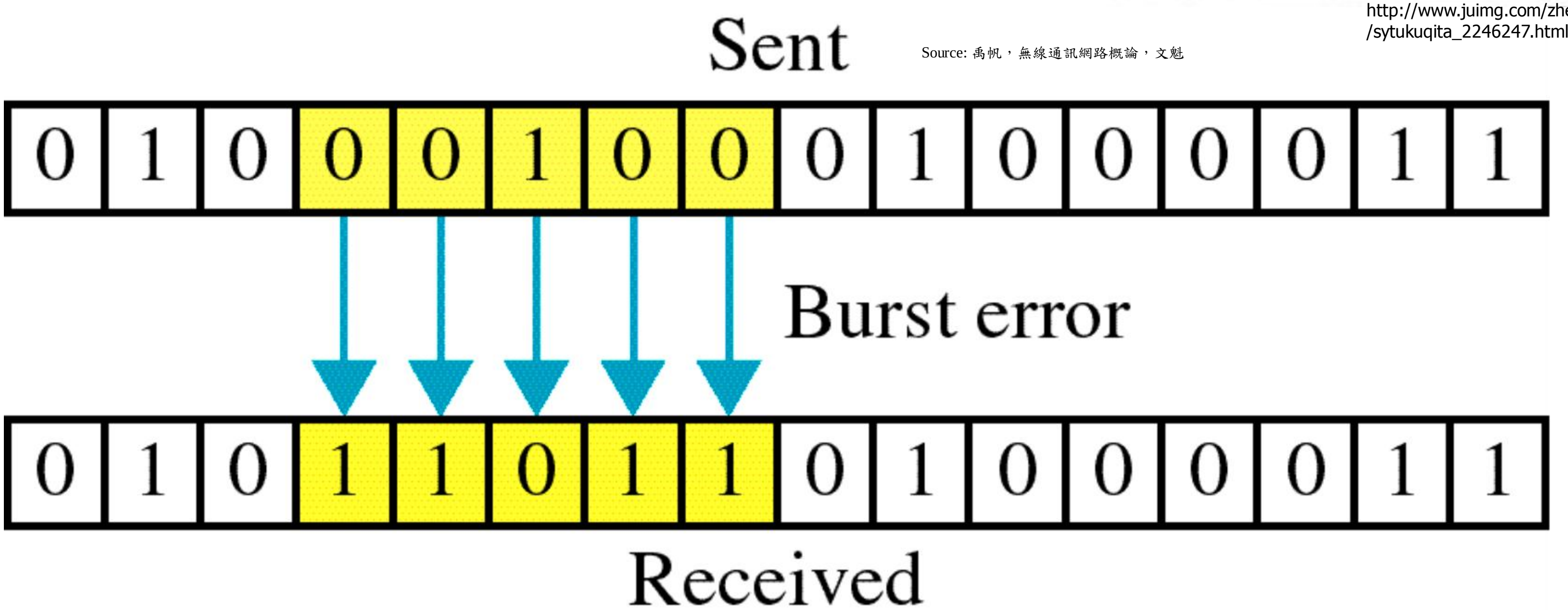
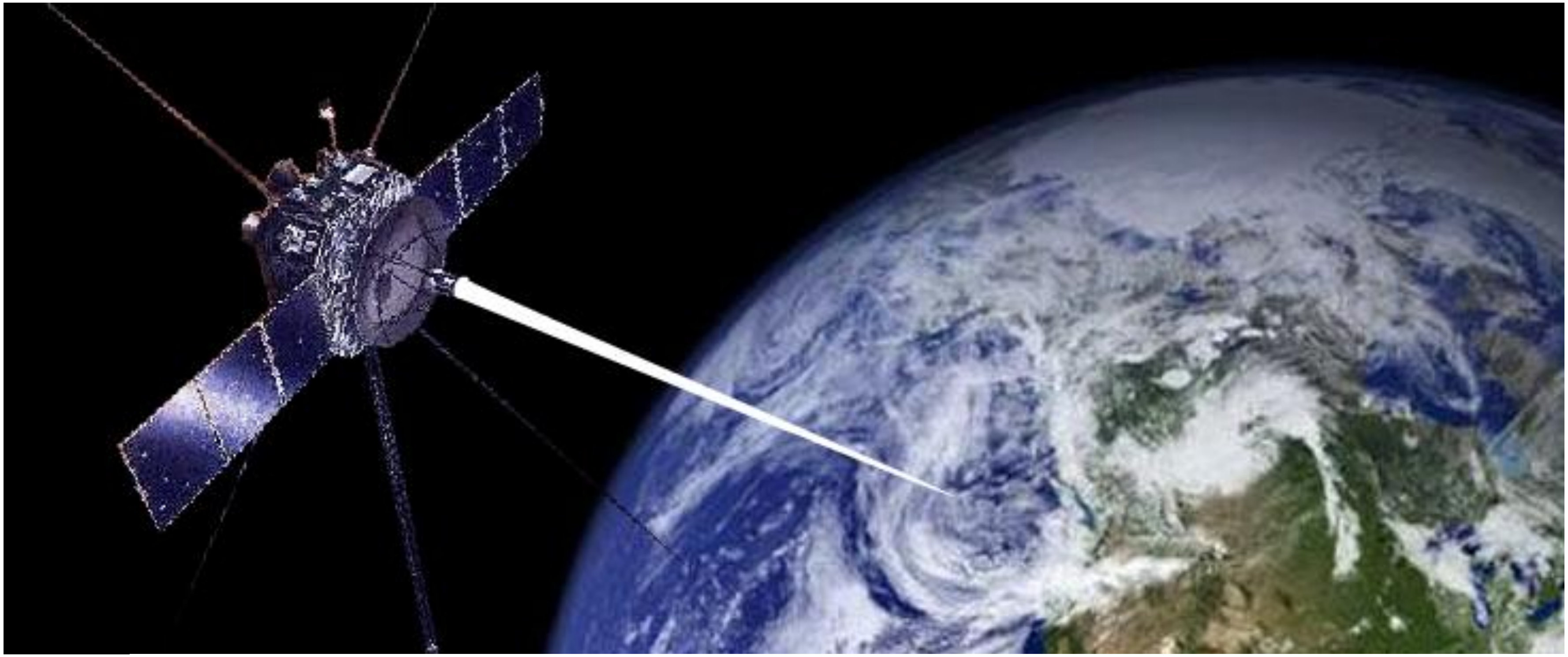
Source: 禹帆，無線通訊網路概論，文魁



4.1. Introduction (cont.)

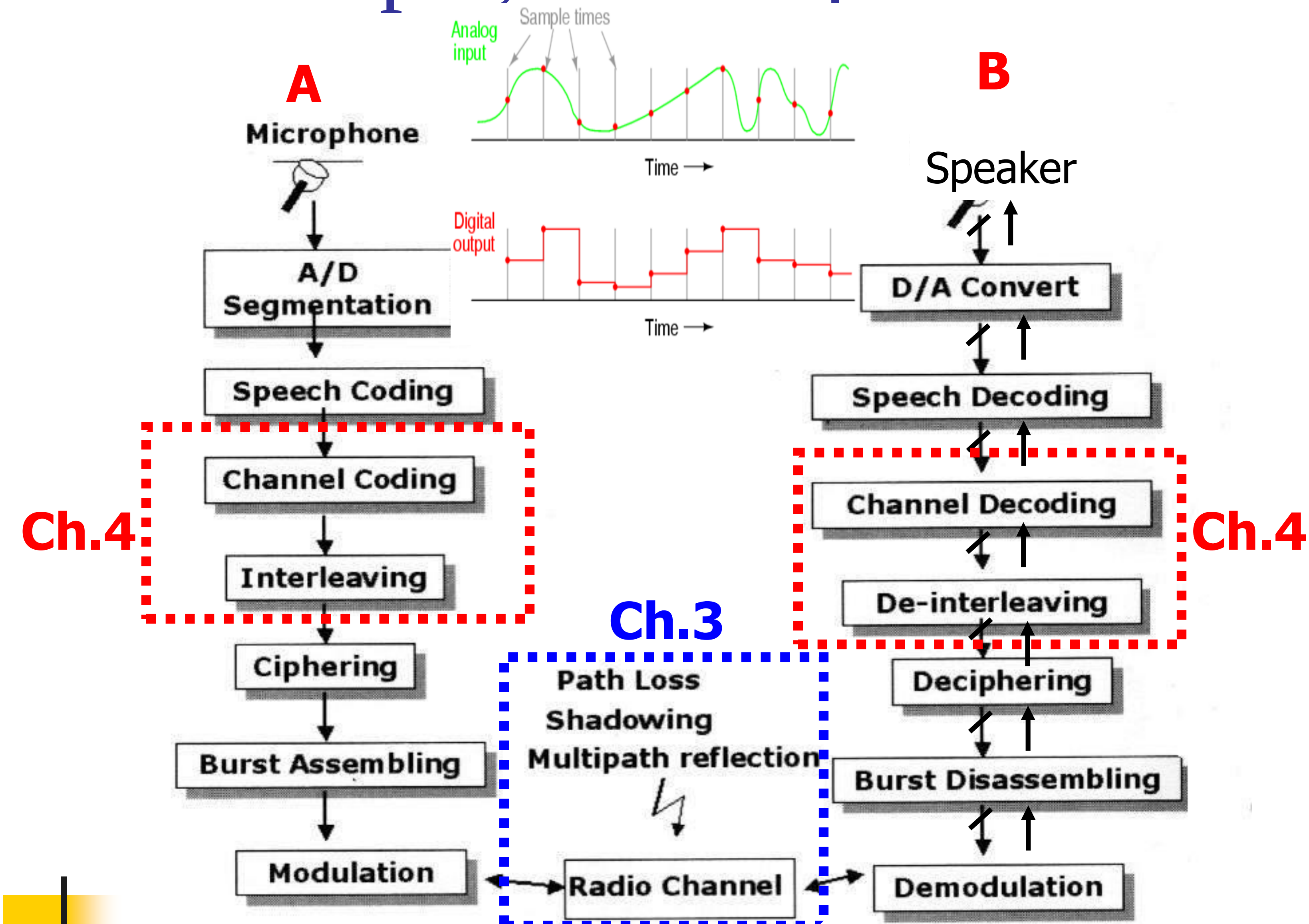
- In **satellite** communications due to:
  - Limited xmitting power for forward channels (downlink)
    - Limited satellite energy resources



=> Need means to **improve transmissions**

Channel coding and **error control** are such means

For example, mobile phone



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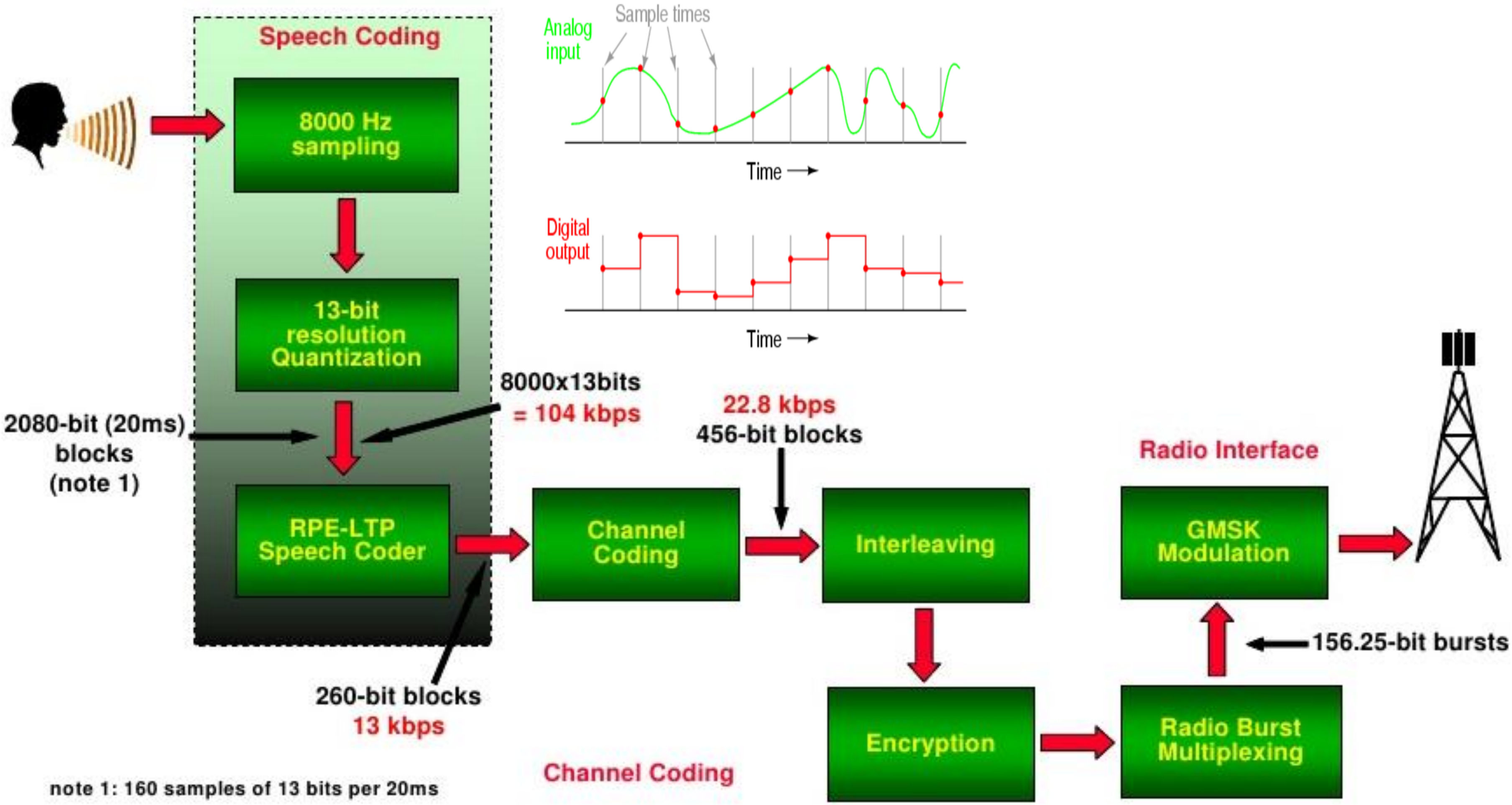
GSM Voice Coding Sequence



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- => Need channel coding and error control to improve transmissions

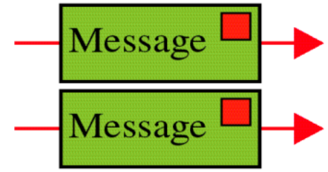
10,000

1,000 ?

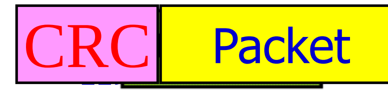
- Channel coding (CC)
  = coding (discrete digital) information into a form suitable for transmission, with emphasis on enhanced **reliability**

http://pansci.asia/wp-content/uploads/2014/04/pp1-560x286.png

http://us.etherwan.com/Download/ePaper/00074/images/MediaConverter_2012.jpg



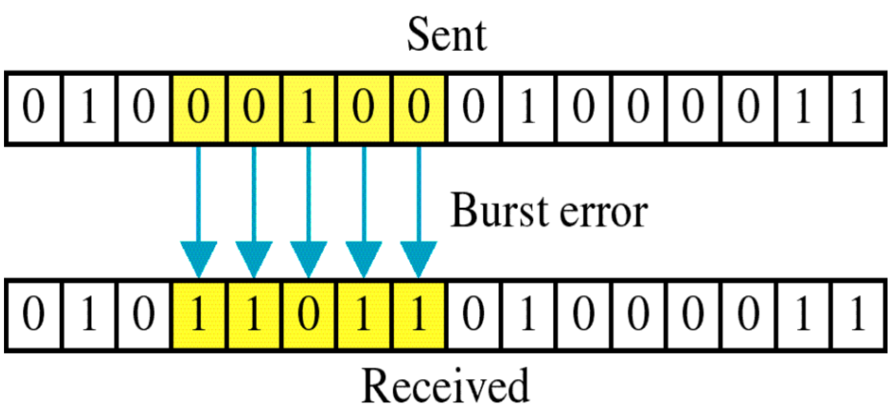
- Channel coding (CC)
  - CC adds **redundancy** that allows for information restoration or recovery when needed



    - Price paid: need **broader bandwidth**

      代價; 運費; 押鏢金

  - CC ensures proper transmission quality
    - Measured by
      - Bit error quality (**BER**) / Frame error quality (**FER**)



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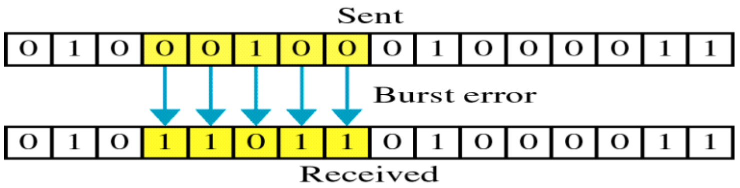
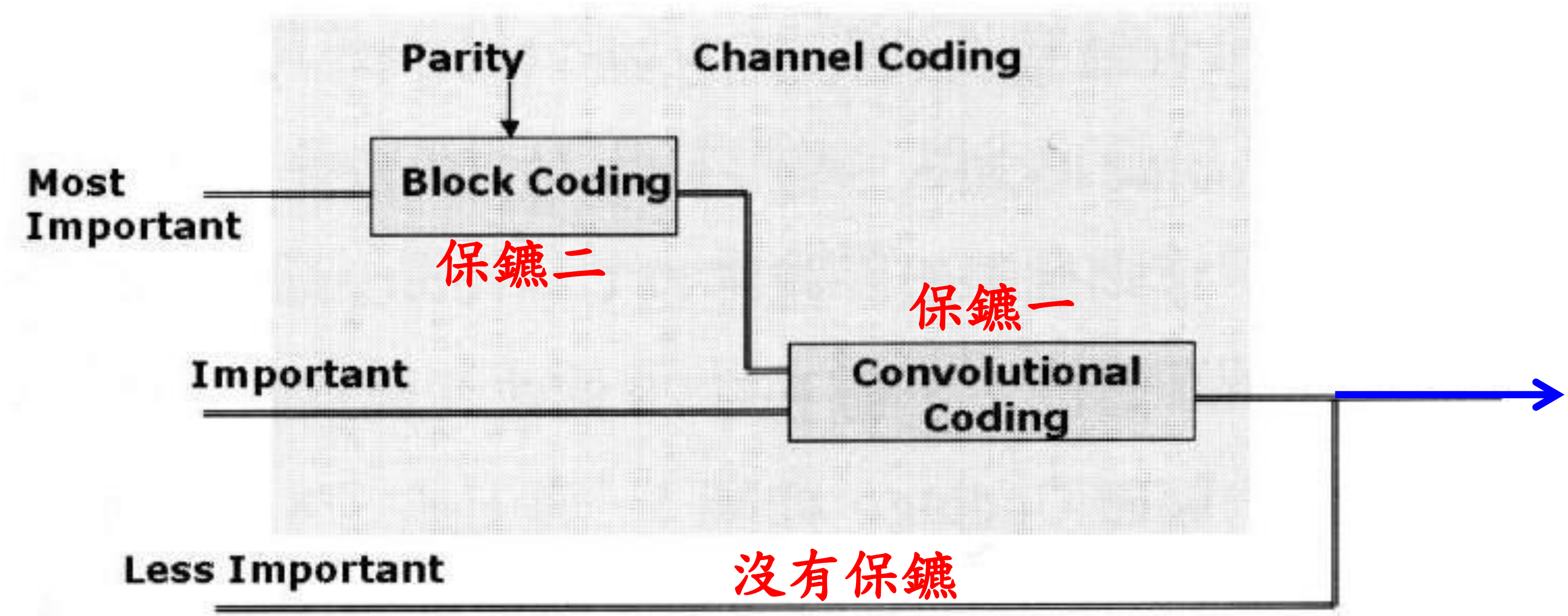
Channel Coding



- Bit Error Rate (BER): 數位系統訊號受干擾的程度
- BER過高➔通話品質下降
  - Error Detection / Error Correction ➔ **Channel Coding**
- GSM TCH channel coding

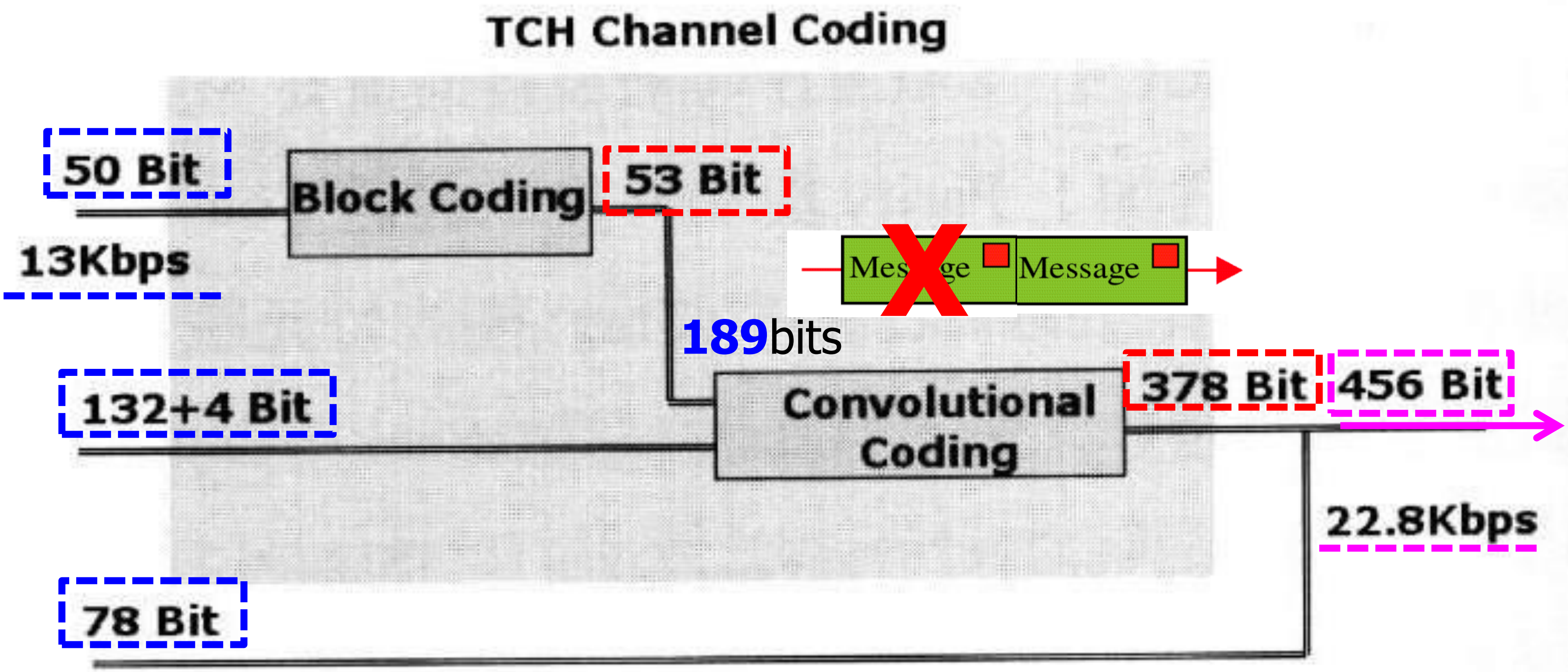


Source: 禹帆，無線通訊網路概論，文魁

Channel Coding (cont.)

- GSM TCH頻道編碼時對260個位元的處理方式

Need broader bandwidth



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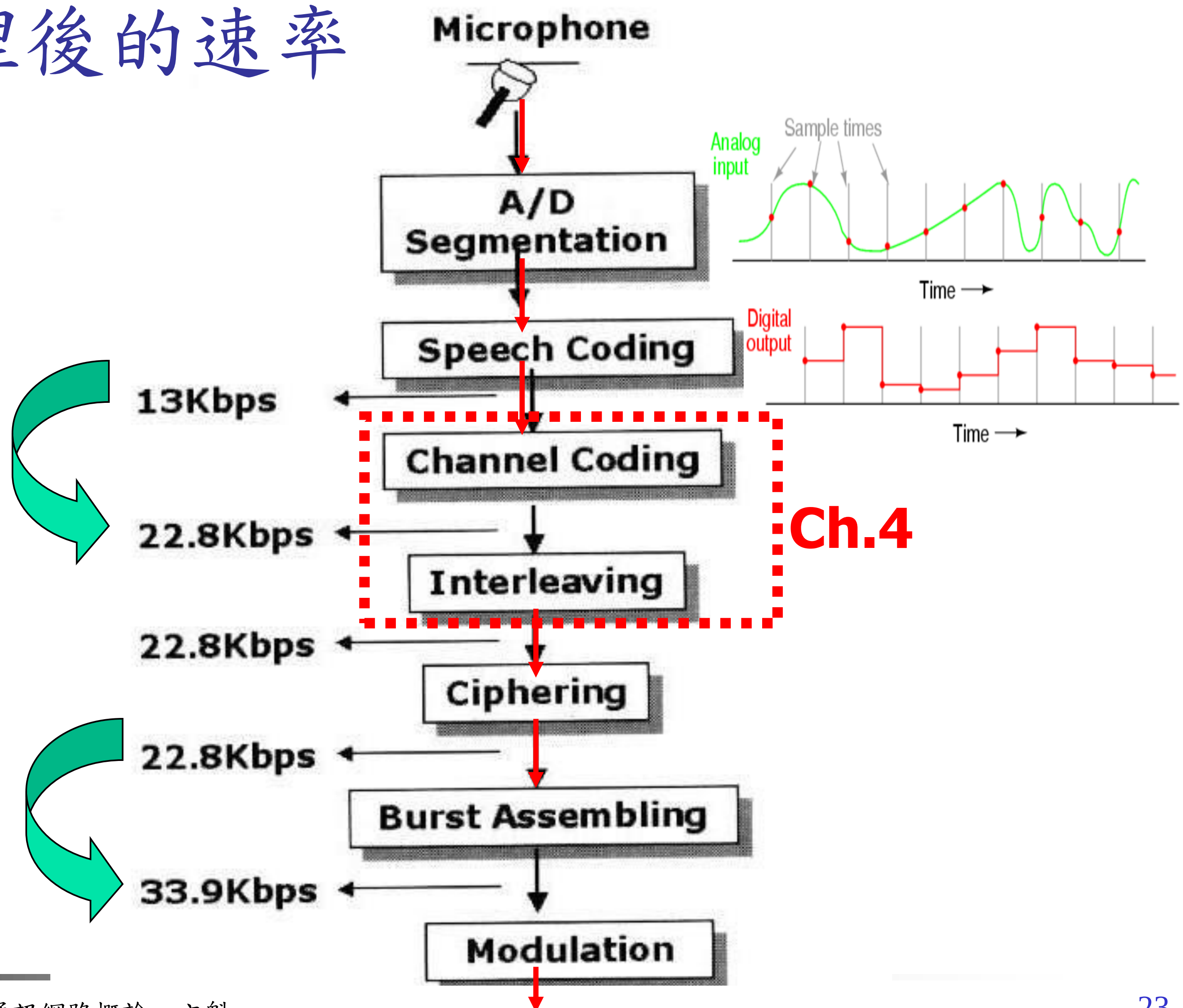
Channel Coding (cont.)

行動電話語音頻道於各個階段經過訊號處理後的速率



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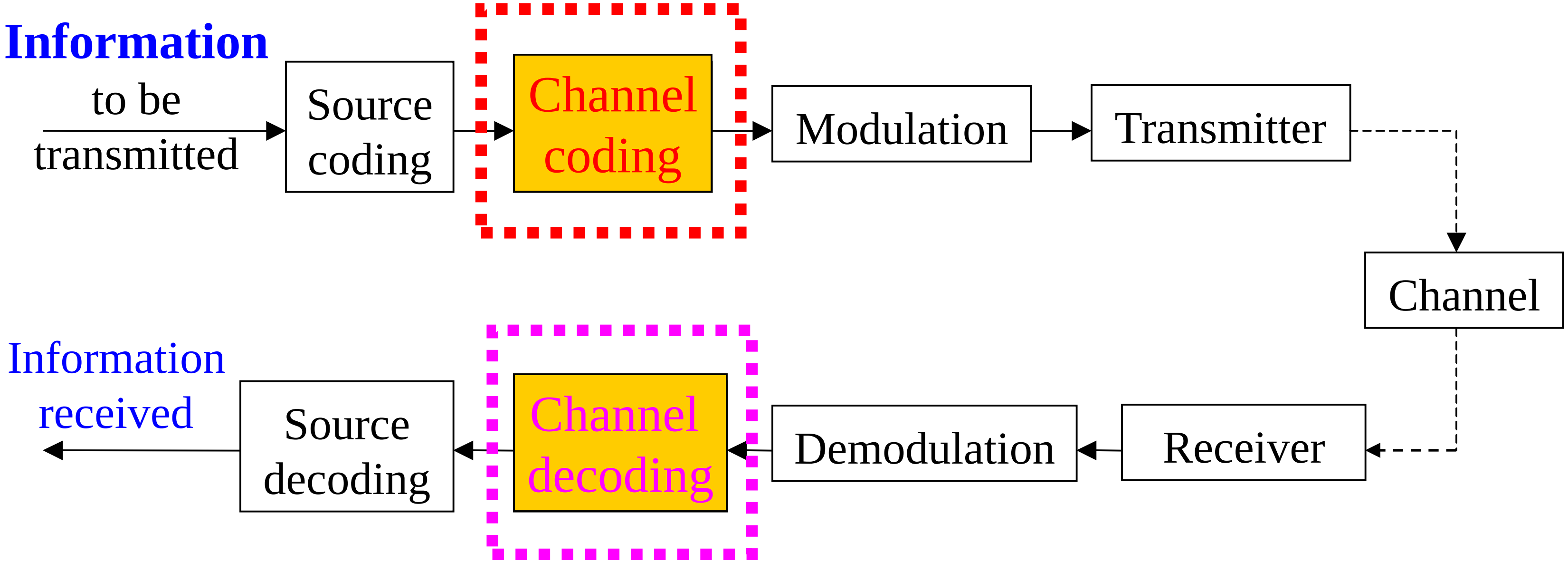
- Channel coding/decoding in a wireless communication system



p. 80 (頁90) Fig. 4.1

Error Control Process (Review)

- All transmission media have potential for introduction of errors
- Error control process has two components
- Error detection

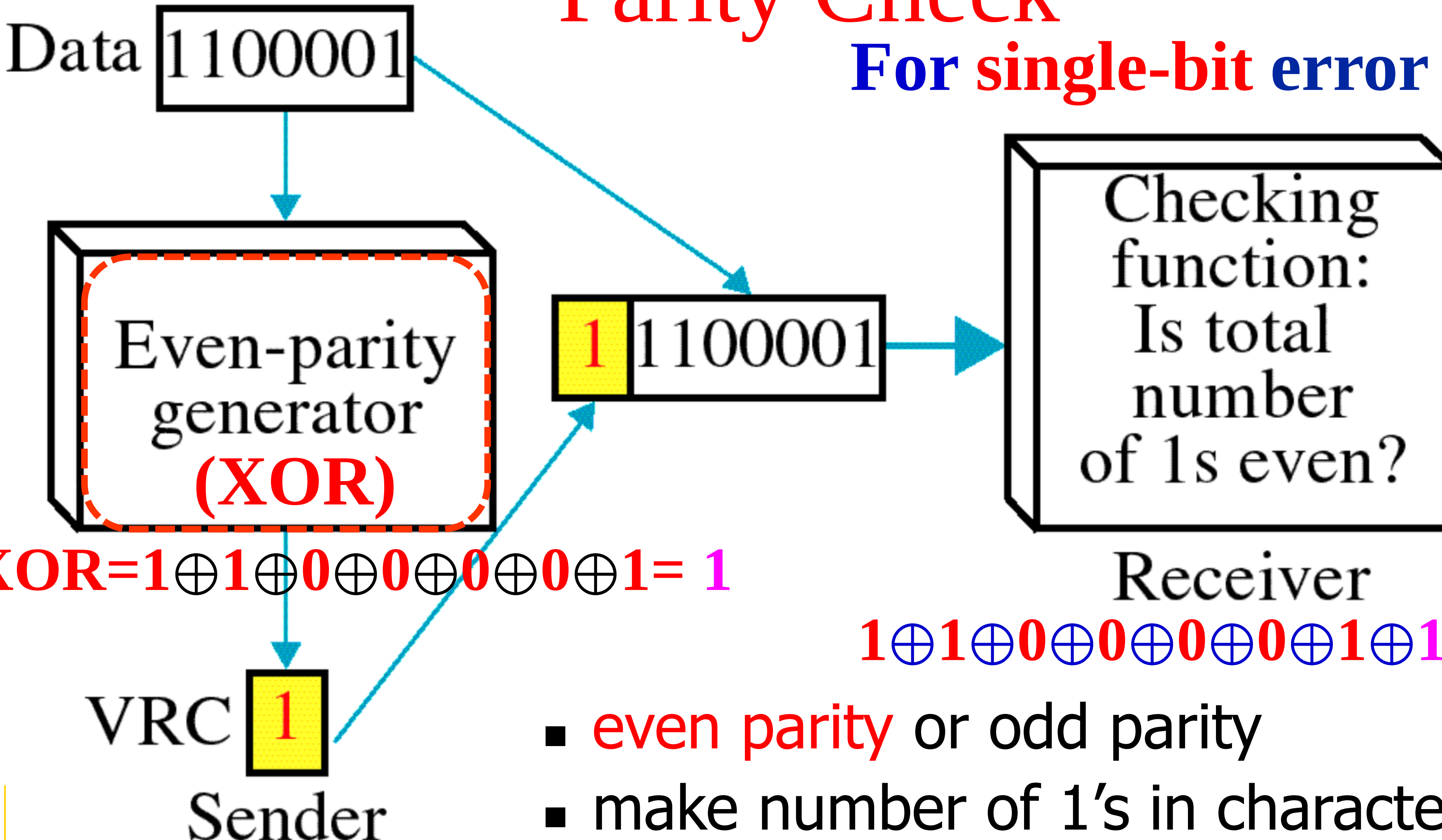
  - redundancy in data so that error can be detected
- Error correction

  - once error detected, frames corrected or retransmitted

Error Detection (Review)

Parity Check

For single-bit error



XOR=1⊕1⊕0⊕0⊕0⊕0⊕1= 1

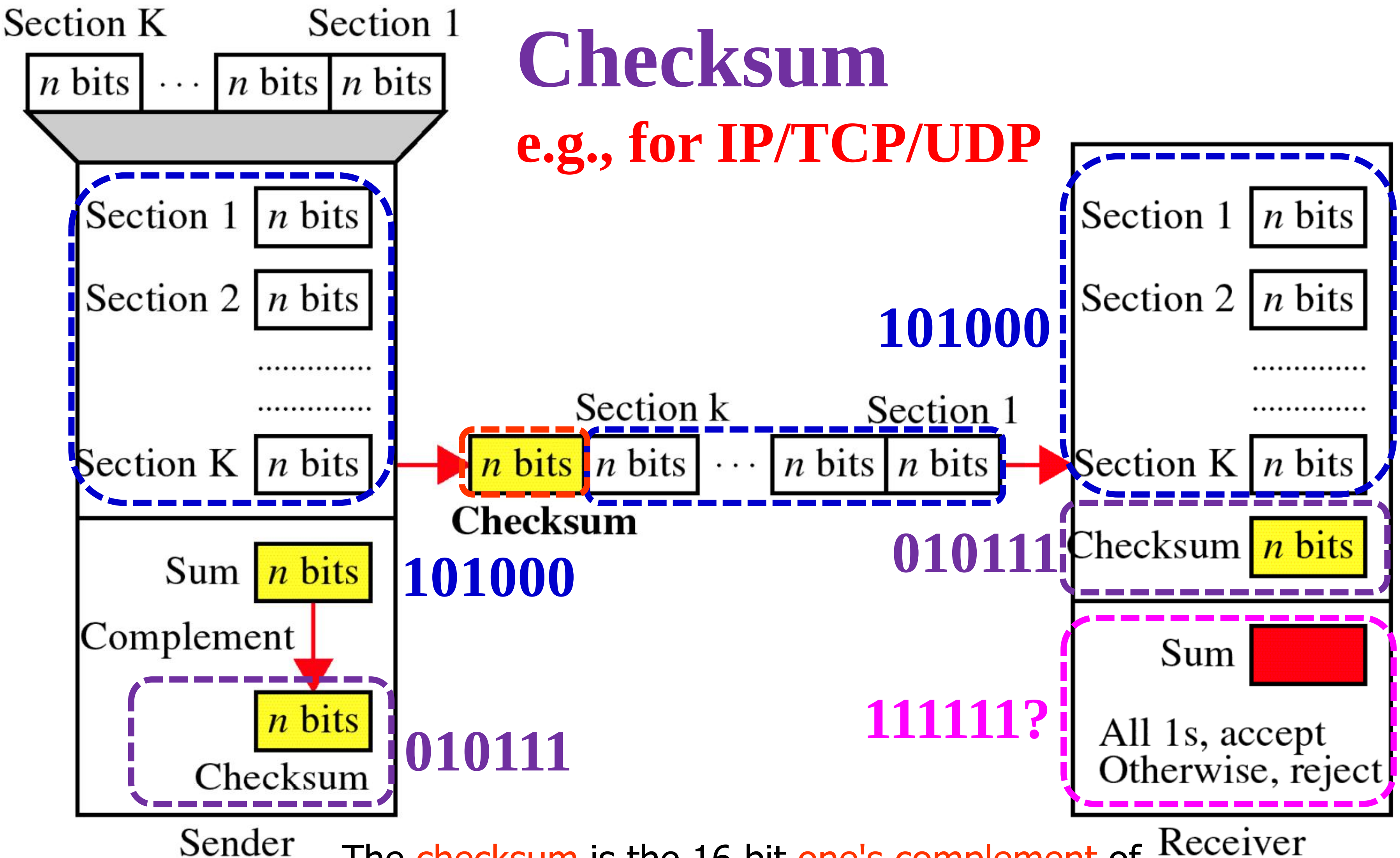
1⊕1⊕0⊕0⊕0⊕0⊕1⊕1=0

- even parity or odd parity
- make number of 1's in character even or odd

Error-Detecting (Review)

Checksum

e.g., for IP/TCP/UDP

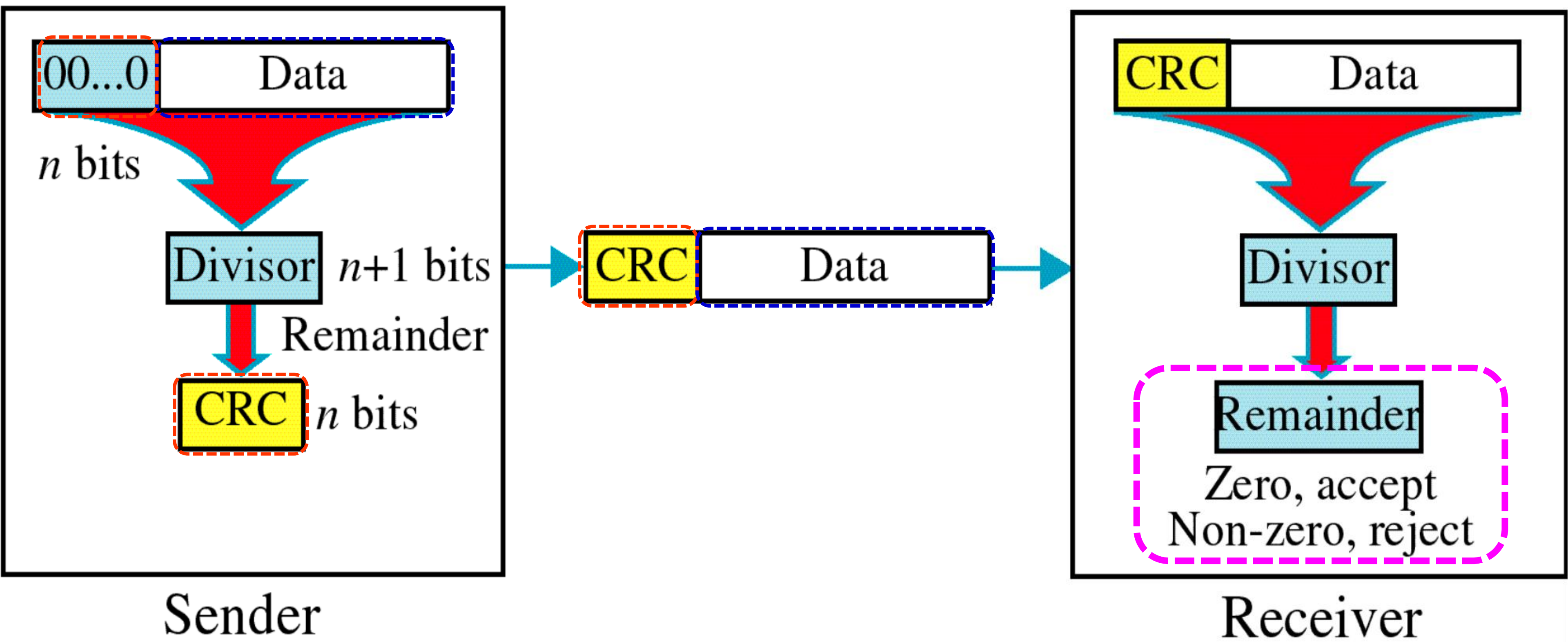


The checksum is the 16 bit one's complement of the one's complement sum of all 16 bit words.

Error-Detecting (Review)

Error-Detecting Codes -- CRC

CRC (Cyclic Redundancy Check)

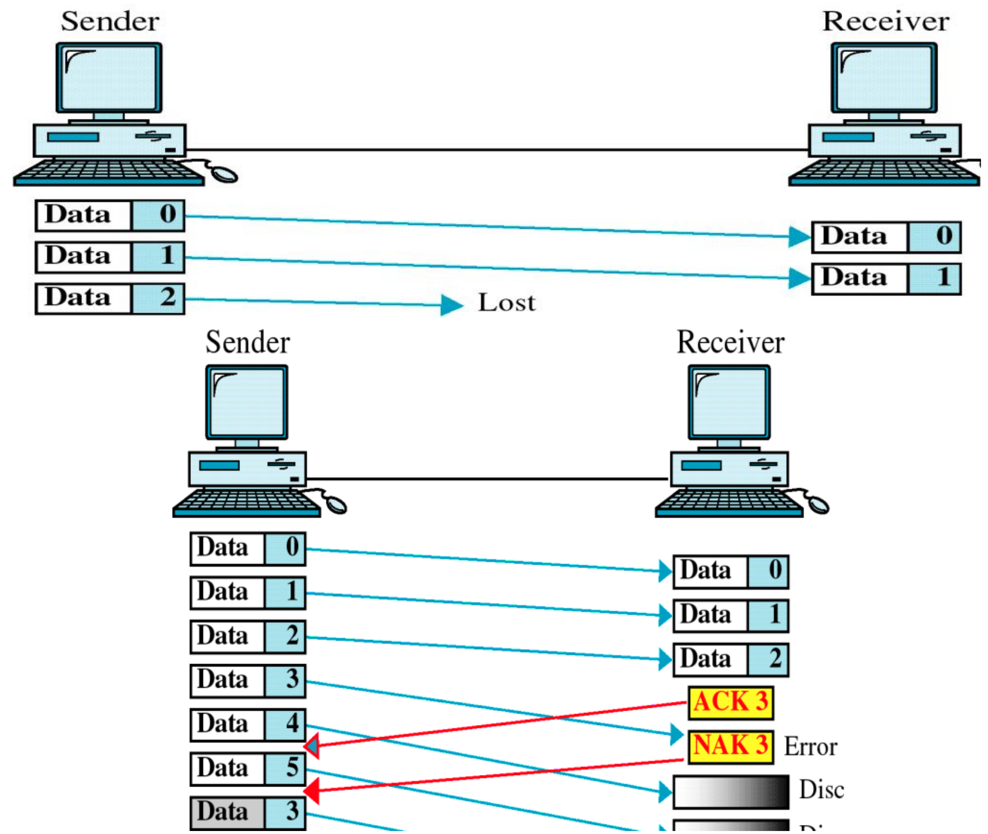


E.g., FCS(Frame Check Sequence)

in Ethernet/ WiFi frame format

Error Correction

- Two types of errors
  - Lost frame –
    never arrives
  - Damaged frame –
    error in bits



- Automatic Repeat reQuest (ARQ)
  - Positive acknowledgment (ACK) if received
  - Retransmission after time-out if not ACK
  - Negative ACK and retransmission if error
- Error-Correcting Codes

Error Correction (EC)

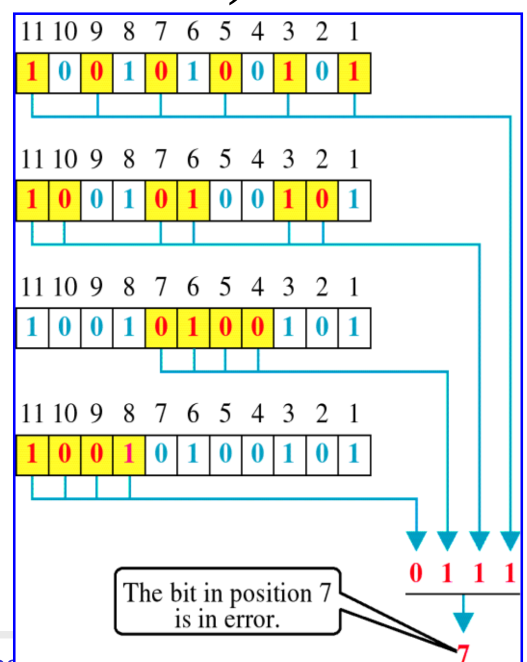
- The key EC idea:

  - Transmit enough redundant data to allow receiver to recover from errors all by itself
    - No sender retransmission required

- Major categories of EC codes （保護的方法與等級）

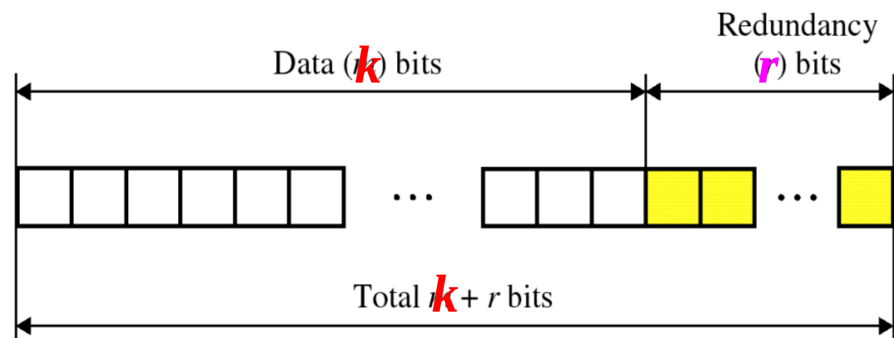
  (really: forward error correction – FEC)

  - Linear block codes
    - Hamming code
    - BCH code
    - Cyclic codes
    - Reed-Solomon codes
  - Convolutional codes (迴旋碼)
  - Turbo codes (渦輪碼)



4.2. Linear Block Codes

- Information is divided into **blocks** of length ***k***
- ***r*** parity bits or check bits are added to each block
  - Total length: $\boldsymbol{n} = \boldsymbol{k} + \boldsymbol{r}$



- Coding rate:

$$\boldsymbol{R} = \boldsymbol{k}/\boldsymbol{n} = k/(k + r)$$

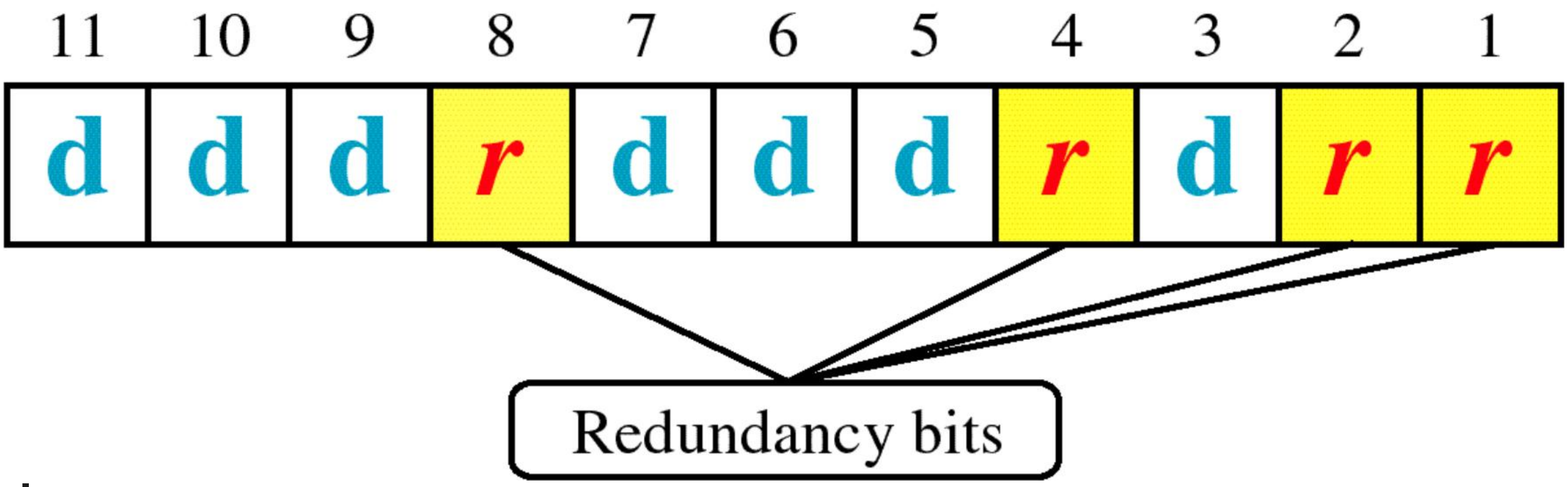
- Decoder looks for code word closest to received vector
  - Received vector = code vector + error vector
- Tradeoffs between
  - Efficiency: ***R***
  - Reliability: 可靠度；判斷正確的程度
  - Encoding/decoding complexity: algorithm

Hamming Code (Review)

n = 11, k = 7, r = 4, R = 7/11

Coding rate

Code word

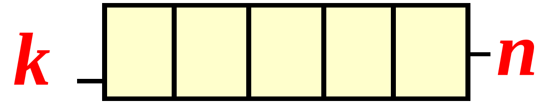


4.5. Convolutional Codes

請功夫最好的保鑣

http://static.apple.nextmedia.com/images/e-paper/20121102/large/1351837530_3133.jpg

- Most commonly used channel codes
  - E.g., in GSM and IS-95
- Encoding of **information stream** rather than information **blocks** **0010011010011010001100…**
  - Output (encoded bits) depends not only on current input bits but also on past data bits
    - M - max. # of (past) stages (a.k.a. memory size) affecting output



  - Easy implementation using shift register
    - Assuming ***k*** inputs and ***n*** outputs
- Decoding most often based on the **Viterbi Algorithm**

 (Modified by LTL)

電動絞肉機

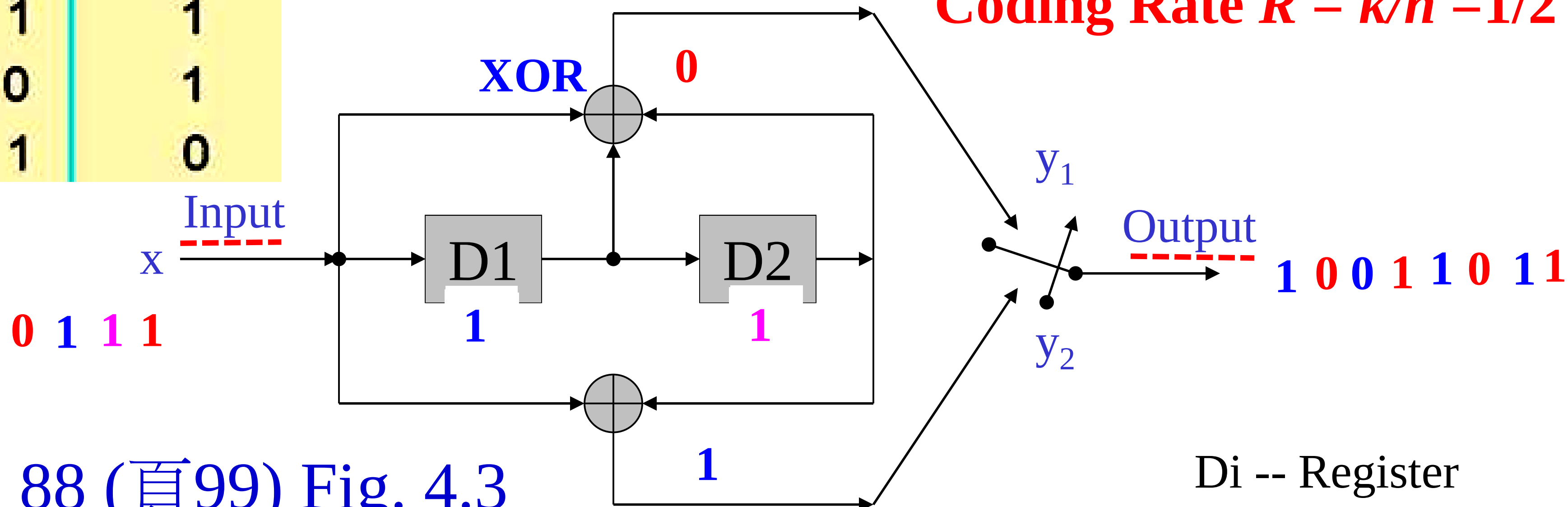
0010011010011010001100

Source: http://att3.citysbs.com/f400x400/hangzhou/2013/04/09/11/110208_18421365476528946_fdd3a35cdf17b7ce100b676050565345.jpg

Convolutional Codes: (k=1, n=2, M=2) Encoder

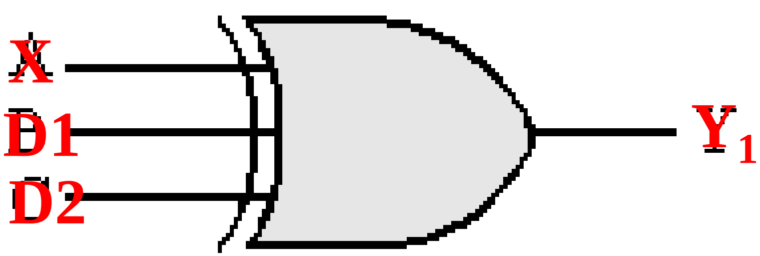
x	y	x XOR y
0	0	0
0	1	1
1	0	1
1	1	0

Coding Rate $R = k/n = 1/2$



Di -- Register

p. 88 (頁99) Fig. 4.3

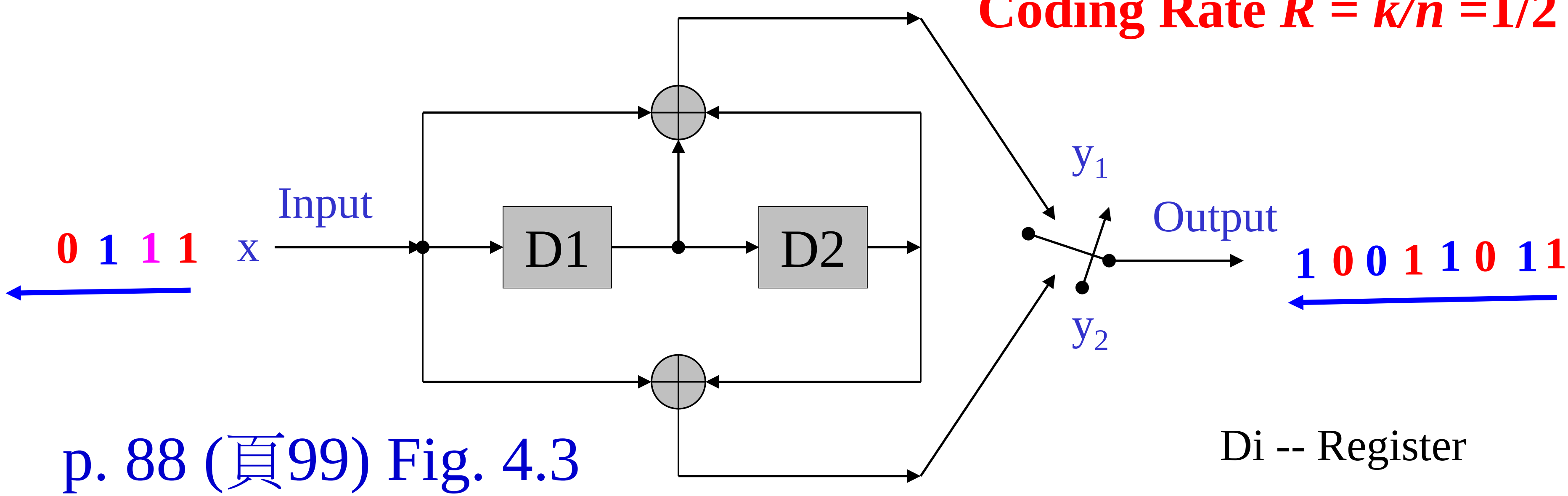


XOR Y_1

x	D1	D2	x XOR D2
0	0	0	0
0	1	1	0
1	0	0	1
1	1	1	1

Convolutional Codes: (k=1, n=2, M=2) Encoder

Coding Rate $R = k/n = 1/2$



p. 88 (頁99) Fig. 4.3

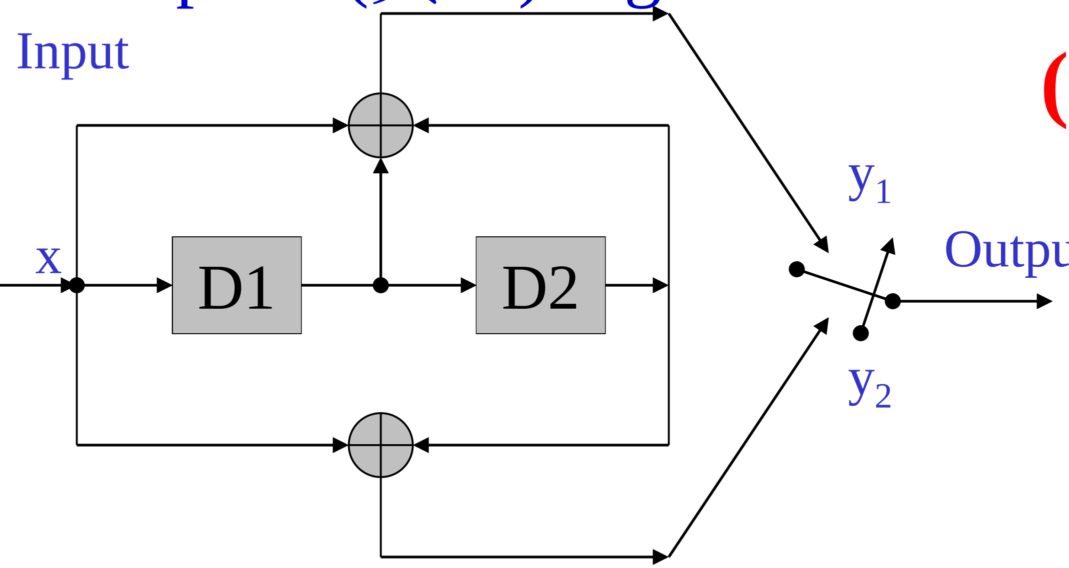
Di -- Register

Input:	1	1	1	0	0	0	…
Output:	11	01	10	01	11	00	…

Input:	1	0	1	0	0	0	…
Output:	11	10	00	10	11	00	…

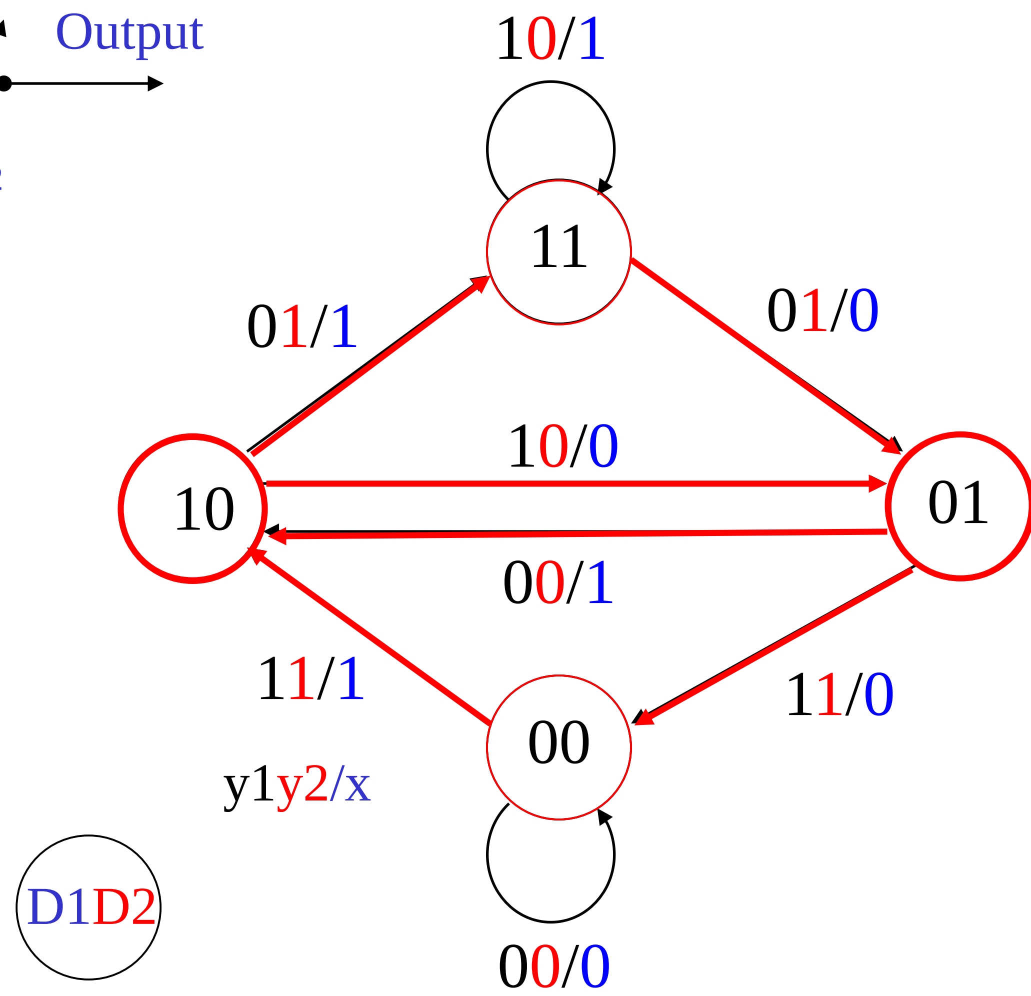
State Diagram (Finite State Machine)

p. 88 (頁99) Fig. 4.3



XOR

x	y	x XOR y
0	0	0
0	1	1
1	0	1
1	1	0



p. 88 (頁100) Fig. 4.4

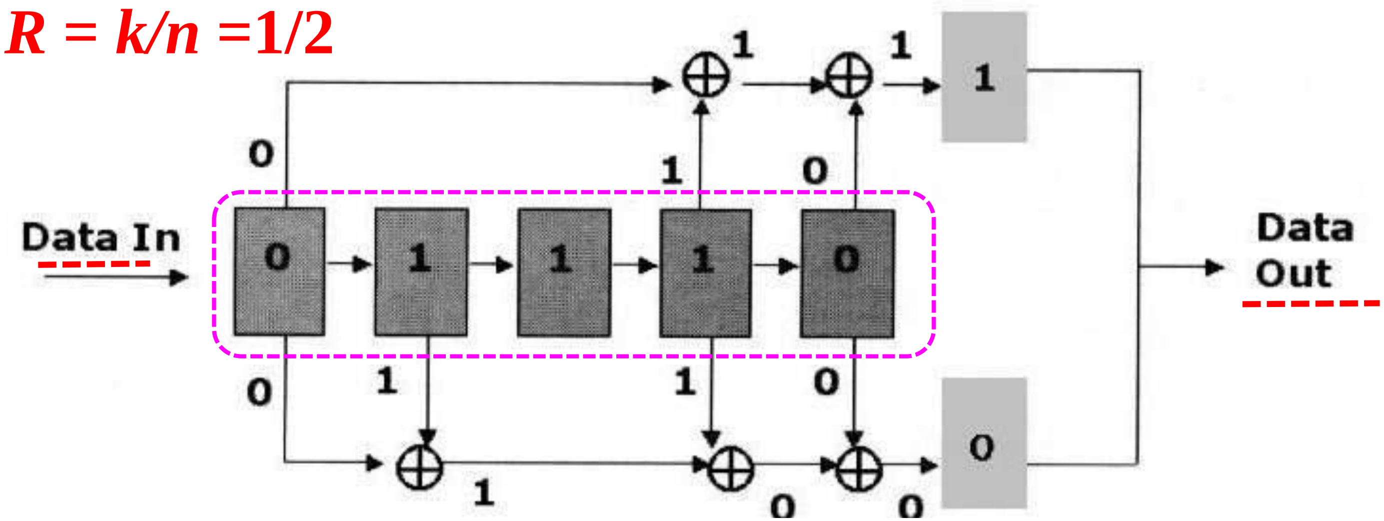
GSM Channel Coding

- Convolutional Coding運用Exclusive OR計算出更多的位元

A	B	A⊕B
0	0	0
0	1	1
1	0	1
1	1	0

Exclusive OR 運算表

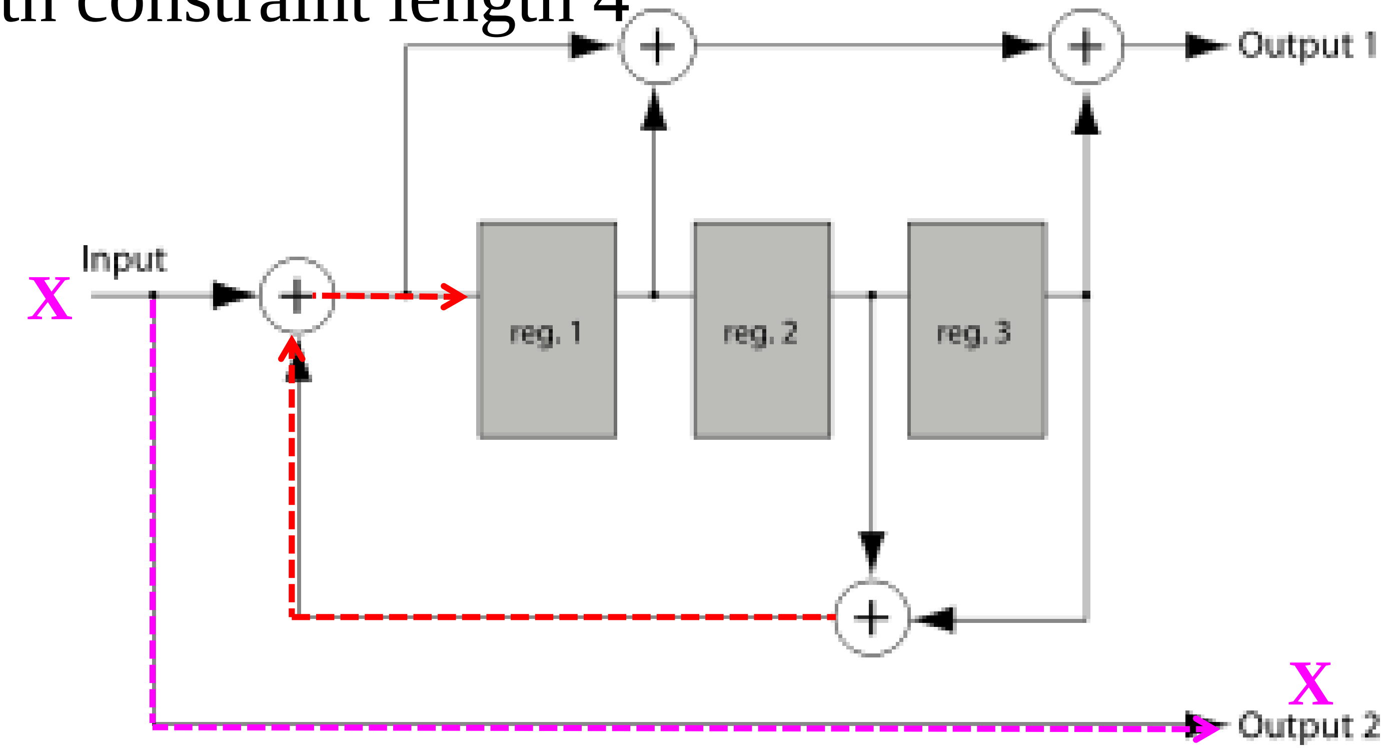
Coding Rate *R* = *k*/*n* =1/2



Source: 禹帆，無線通訊網路概論，文魁

Example 3: **RSC** encoder

- Rate 1/2 recursive, systematic convolutional (**RSC**) encoder with constraint length 4



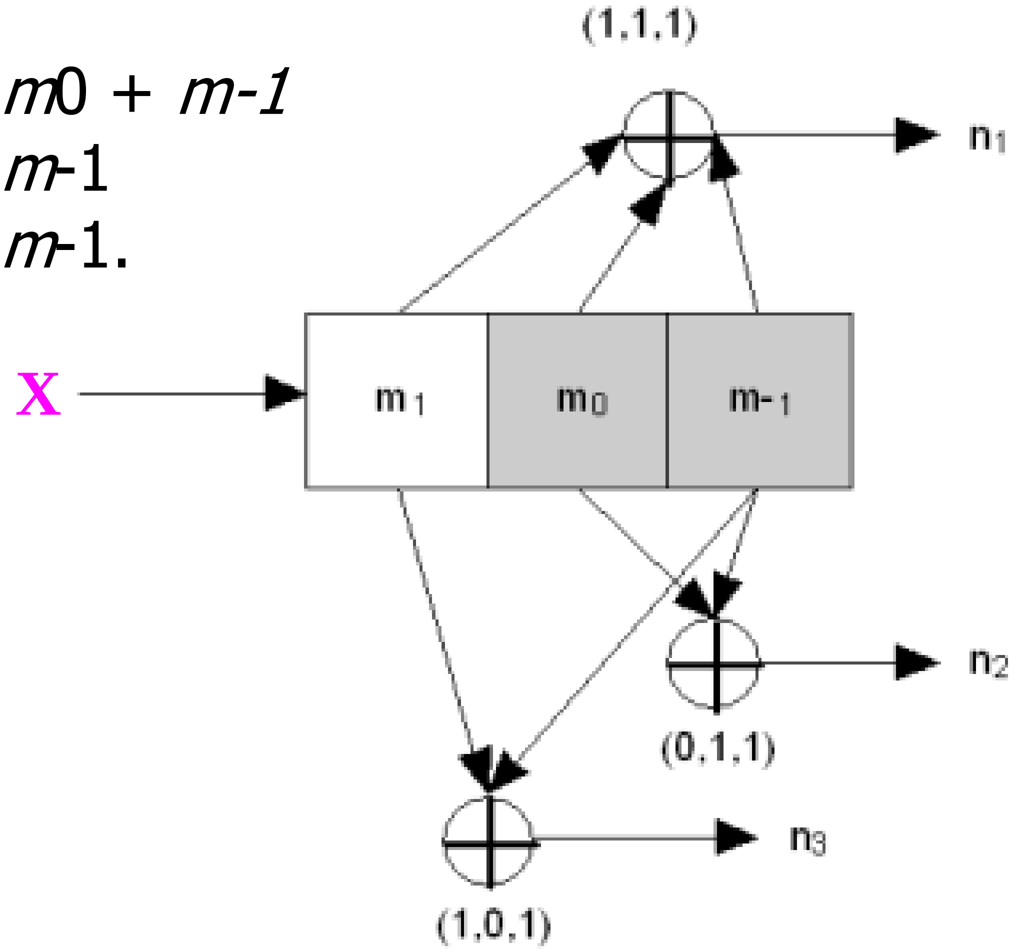
One can see that the input being encoded is included in the output sequence too (look at the output 2). Such codes are referred to as *systematic*; otherwise the code is called *non-systematic*.

Source: http://en.wikipedia.org/wiki/Convolutional_code

Example 2: *non-recursive* encoder

- Rate 1/3 non-recursive, non-systematic convolutional encoder with constraint length 3

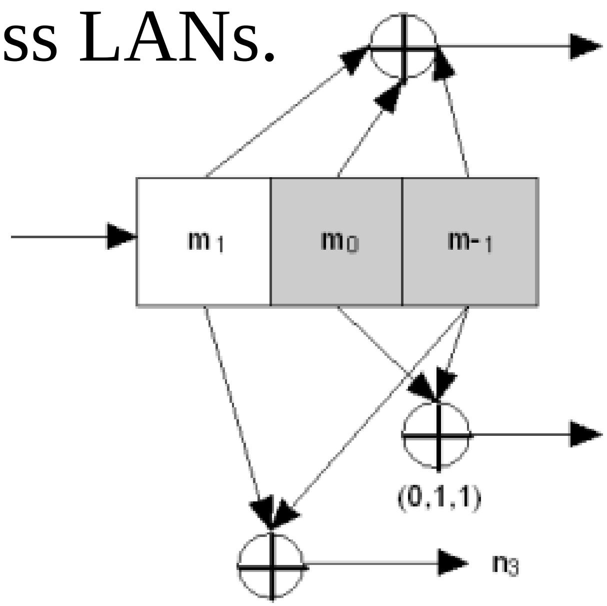
$n_1 = m_1 + m_0 + m_{-1}$
$n_2 = m_0 + m_{-1}$
$n_3 = m_1 + m_{-1}$.



Source: http://en.wikipedia.org/wiki/Convolutional_code

Viterbi Decoding Algorithm

- The Viterbi algorithm was conceived by Andrew Viterbi in 1967 as an error-correction scheme for noisy digital communication links, finding universal application in decoding the convolutional codes used in both CDMA and GSM digital cellular, dial-up modems, satellite, deep-space communications, and 802.11 wireless LANs.

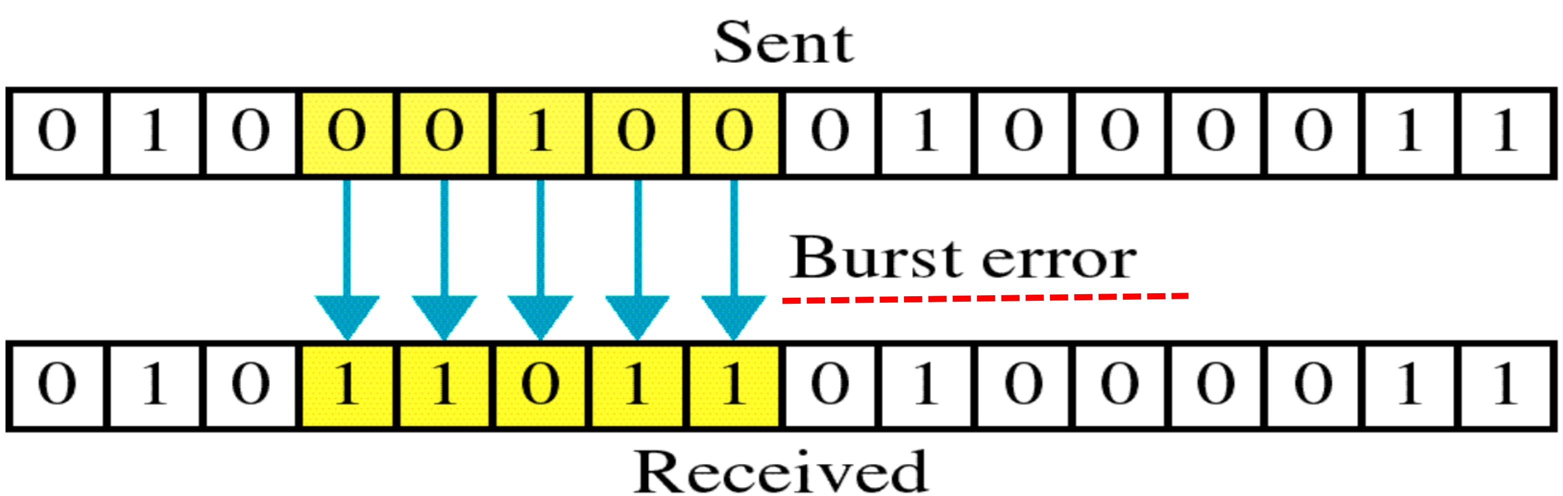


Source: http://en.wikipedia.org/wiki/Viterbi_algorithm

4.6. Interleaver

- Interleaving is heavily used in wireless communication for protection against burst errors
  - Recall:
    Burst error – a contiguous sequence of symbols, received over a data transmission channel, such that:

- Block interleaver - most common interleaver
  - Concept – next slide



Concept of Interleaver

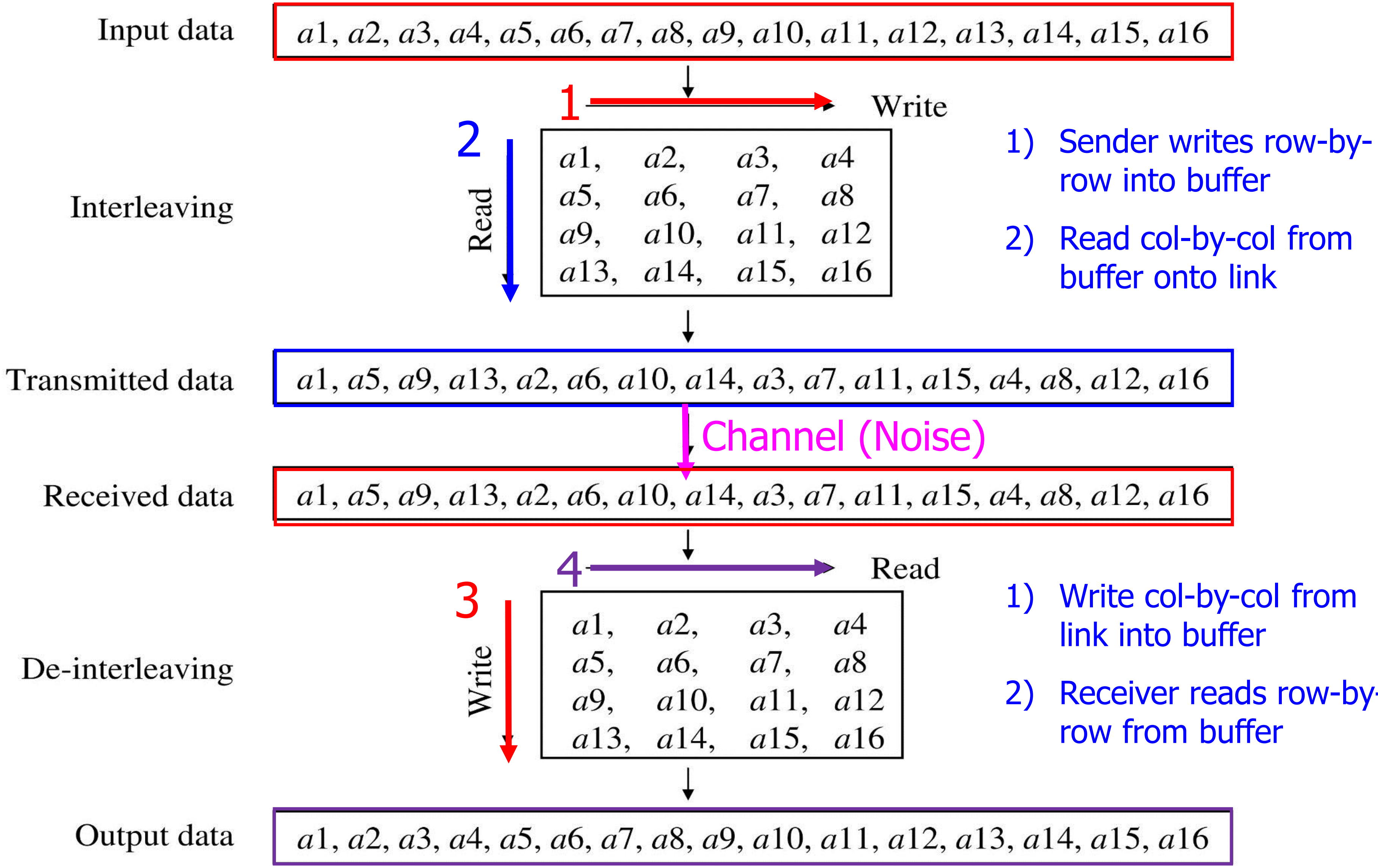


Figure 4.7 Concept of interleaver.

p. 90 (頁102) Fig. 4.7

Interleaving (Example)

Receiver:

Channel (Noise)

Burst error

Transmitting Data: 0, 0, 0, 1, 1, 1, 1, 0, 0, 0, 0,…

Read →

De-Interleaving (Write ↓)

0,	1,	0,	0
0,	1,	0,	0
0,	1,	0,	0
1,	0,	0,	0

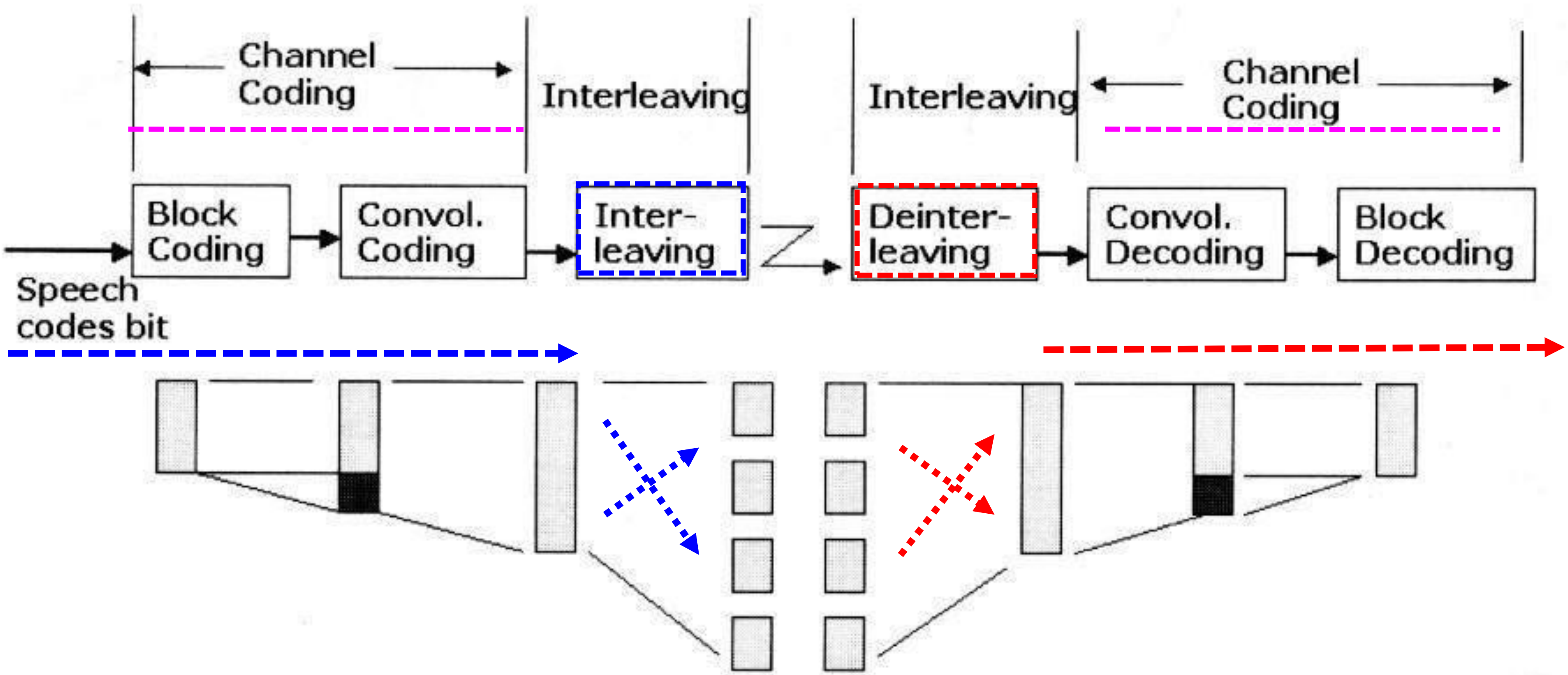
Output Data: 0, 1, 0, 0, 0, 1, 0, 0, 0, 1, 0, 0, 1, …

Discrete error

p. 91 (頁102) Fig. 4.8

Channel Interleaving

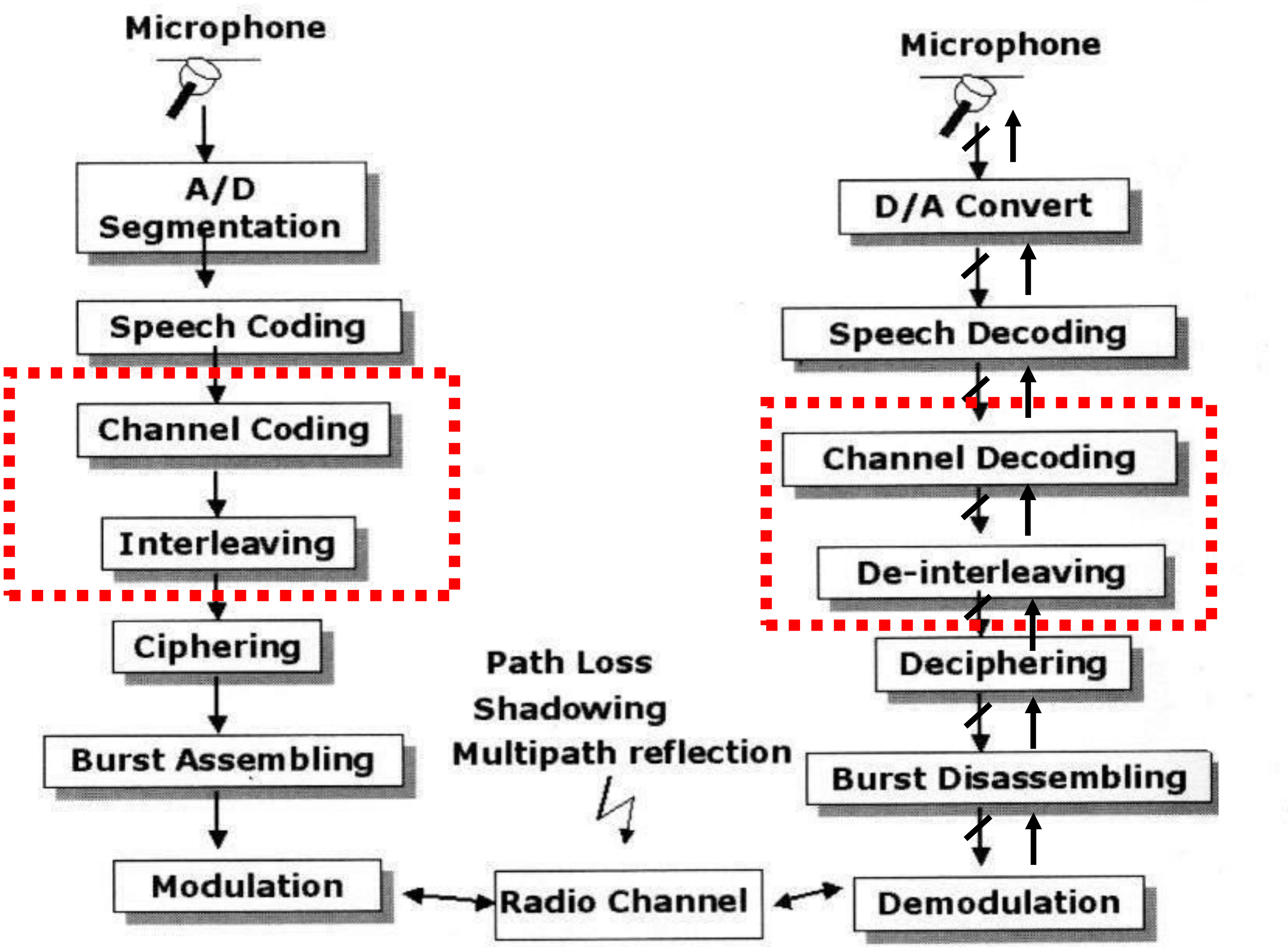
- 頻道編碼(Channel Coding)與交錯(Interleaving)對資料的切割方式



Source: 禹帆，無線通訊網路概論，文魁

Channel Coding (cont.)

- For example, GSM



Source: 禹帆，無線通訊網路概論，文魁

4.7. Turbo Codes

- Brief history of turbo codes:
  - First introduced by C. Berrou *et al*. only in 1993
  - Considered as the most efficient FEC coding schemes
    - Performance close to the (perfect) **Shannon Limit** at modest complexity!
- Turbo codes use known components
  - Including: simple convolutional or block codes, interleaver, soft-decision decoder
- Turbo codes proposed for
  - Low-power applications
    - Such as deep-space and satellite communications,
  - Interference-limited applications
    - Such as 3G cellular, PCS (personal communication services), ad hoc networks and sensornets

Information Capacity Theorem

- Bit Rate: 單位時間內傳送的位元數目，bps
- Baud Rate: 載波之頻率或相位的變化率，Hertz
- Nyquist Theory: $C = 2B$ (ideal channel)
  - C: 載波最高的傳輸率，bps
  - B: 通訊頻道的頻寬，Hz
  - 例：1 GSM 頻道 = 200kHz = B

    載波傳輸率上限 $C = 2B = 400$kbps

Information Capacity Theorem (cont.)

- **Shannon's theorem:**
  - $C = B \cdot \log_2(1+S/N)$ (noisy channel)
  - C: 頻道的數據傳輸率，bps
  - B: 通訊頻道的頻寬，Hz
  - 例：1 GSM 頻道 = 200kHz = B

    S/N = 2.56

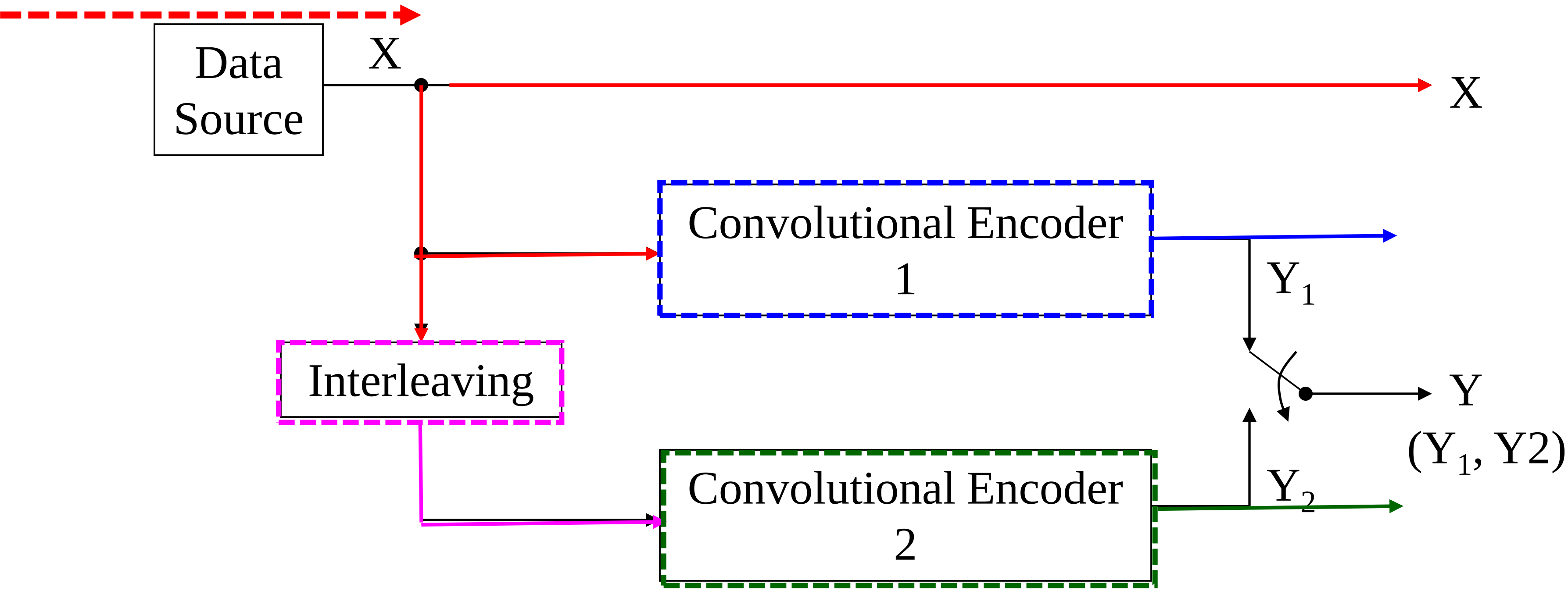
    數據傳輸率上限 C = 200k*lg(2.56) = 271 kbps

    S/N = 10 (剛好10 dB)

    數據傳輸率上限 C = 200k*lg(11) = 692 kbps

利用換底公式: $$\lg(2.56) = \log_2(2.56) = \frac{\log(2.56)}{\log(2)} = \frac{0.40824}{0.30103} = 1.356$$

Turbo Codes: Encoder



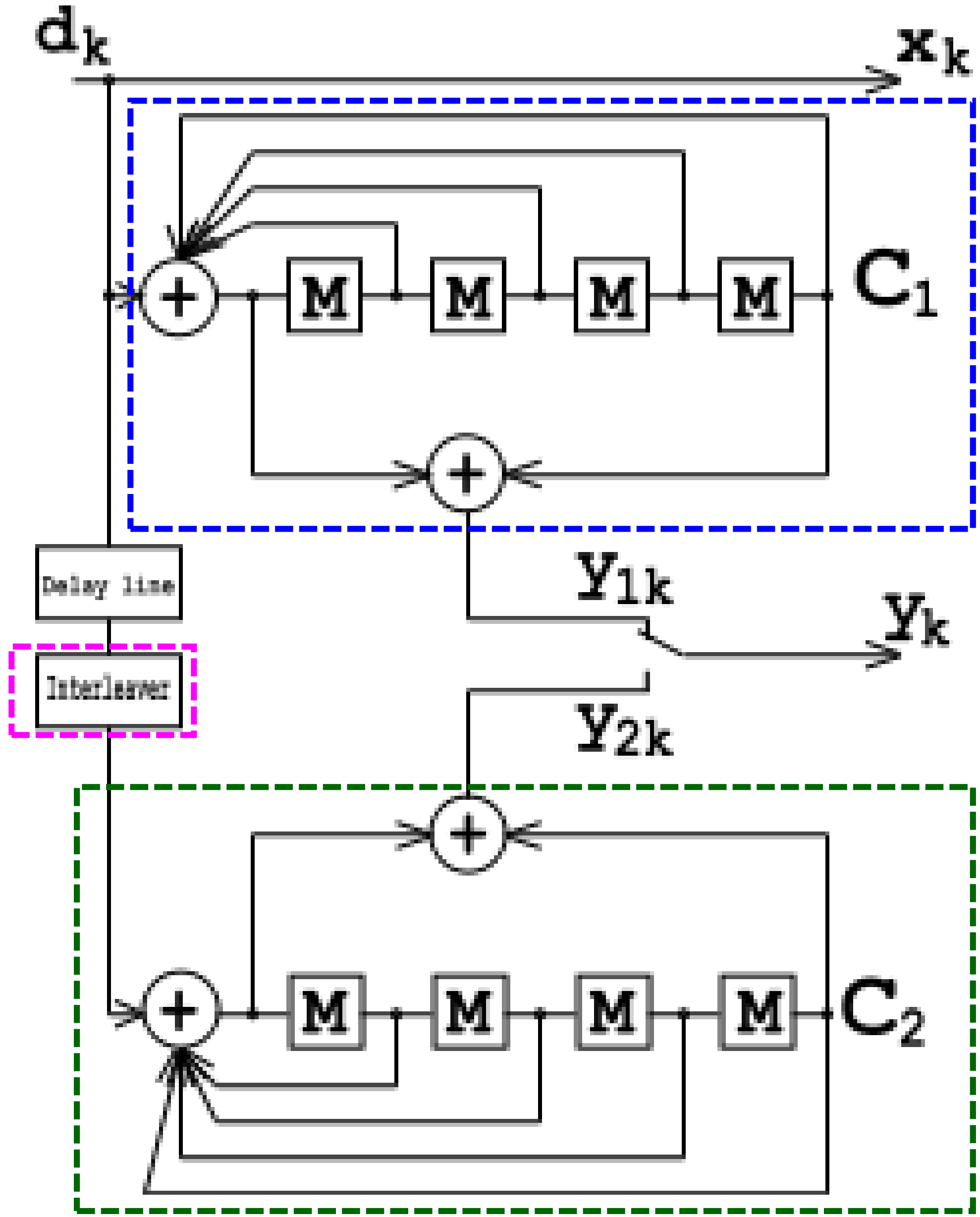
X: Information

Y_i: Redundancy Information

p. 92 (頁103) Fig. 4.9

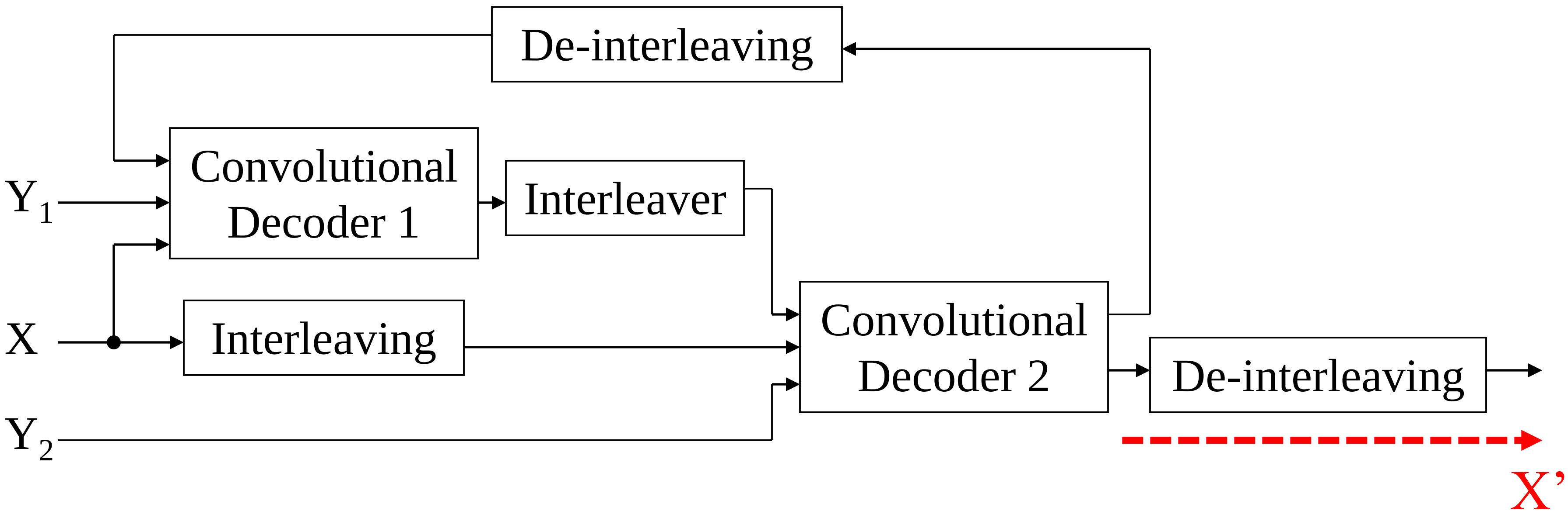
Example of Turbo-code Encoder

- Hardware-wise, this turbo-code encoder consists of two identical **RSC** coders, C1 and C2, as depicted on the figure, which are connected to each other using a concatenation scheme, called *parallel concatenation*



Source: http://en.wikipedia.org/wiki/Turbo_code

Turbo Codes: Decoder

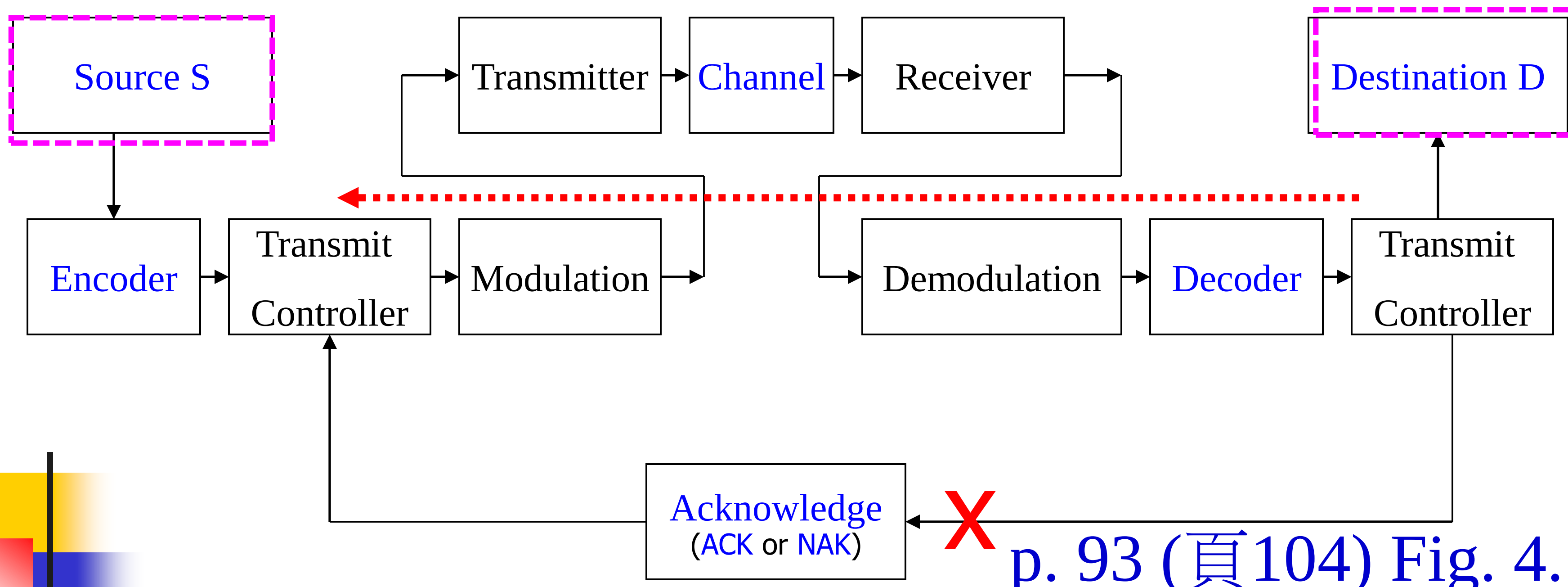


X': Decoded Information

p. 92 (頁104) Fig. 4.10

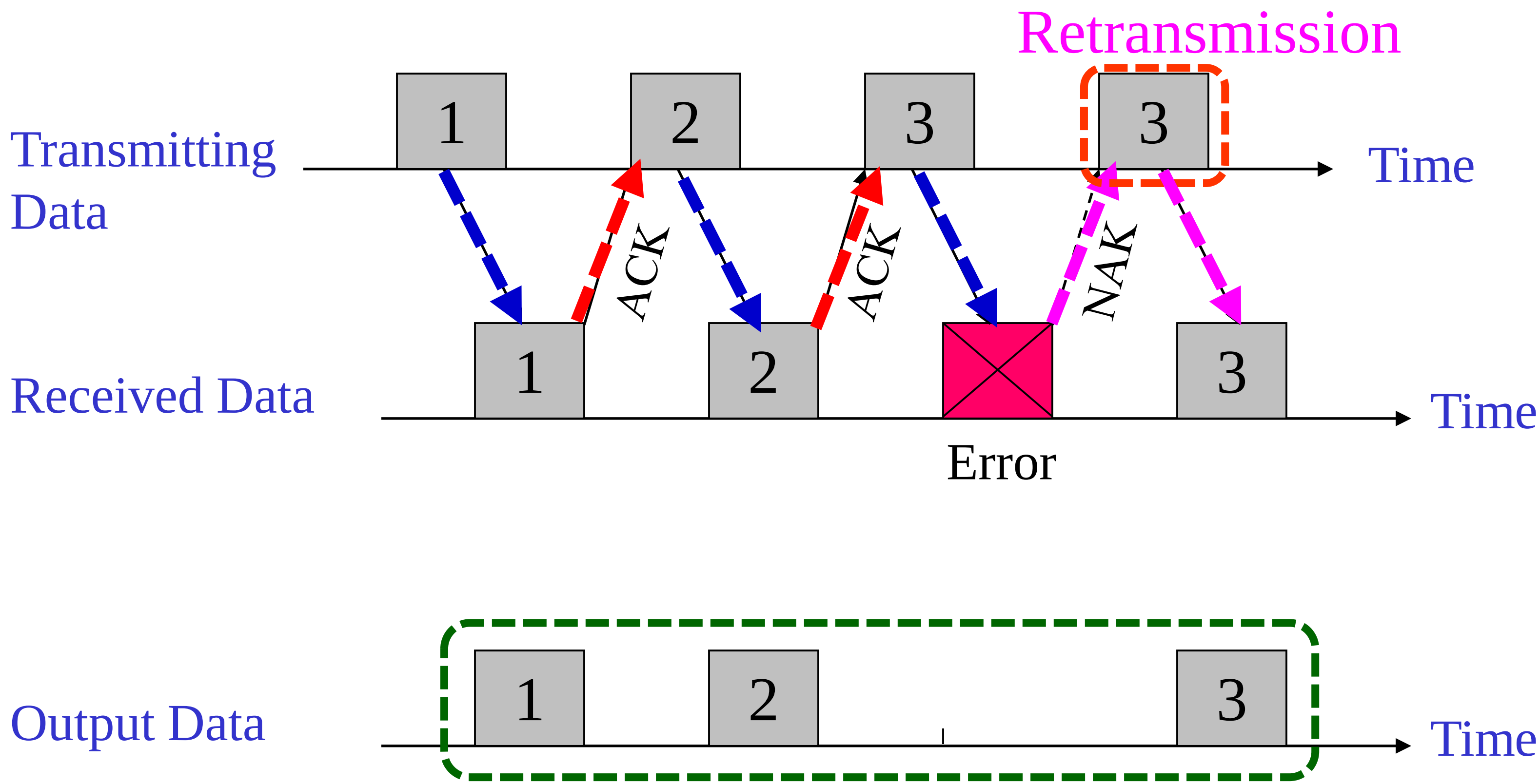
4.8. Automatic Repeat Request (ARQ)

- [LTL] Sometimes Cyclic Code can detect but can't correct errors
  - Must ask for retransmission
  - Can use Automatic Repeat Request (ARQ)
    - D sends (positive) acknowledgement ACK if received packets correct
    - If D detects error it can't correct, D sends negative acknowledgement NAK – this requests retransmission



p. 93 (頁104) Fig. 4.11

Stop-And-Wait ARQ



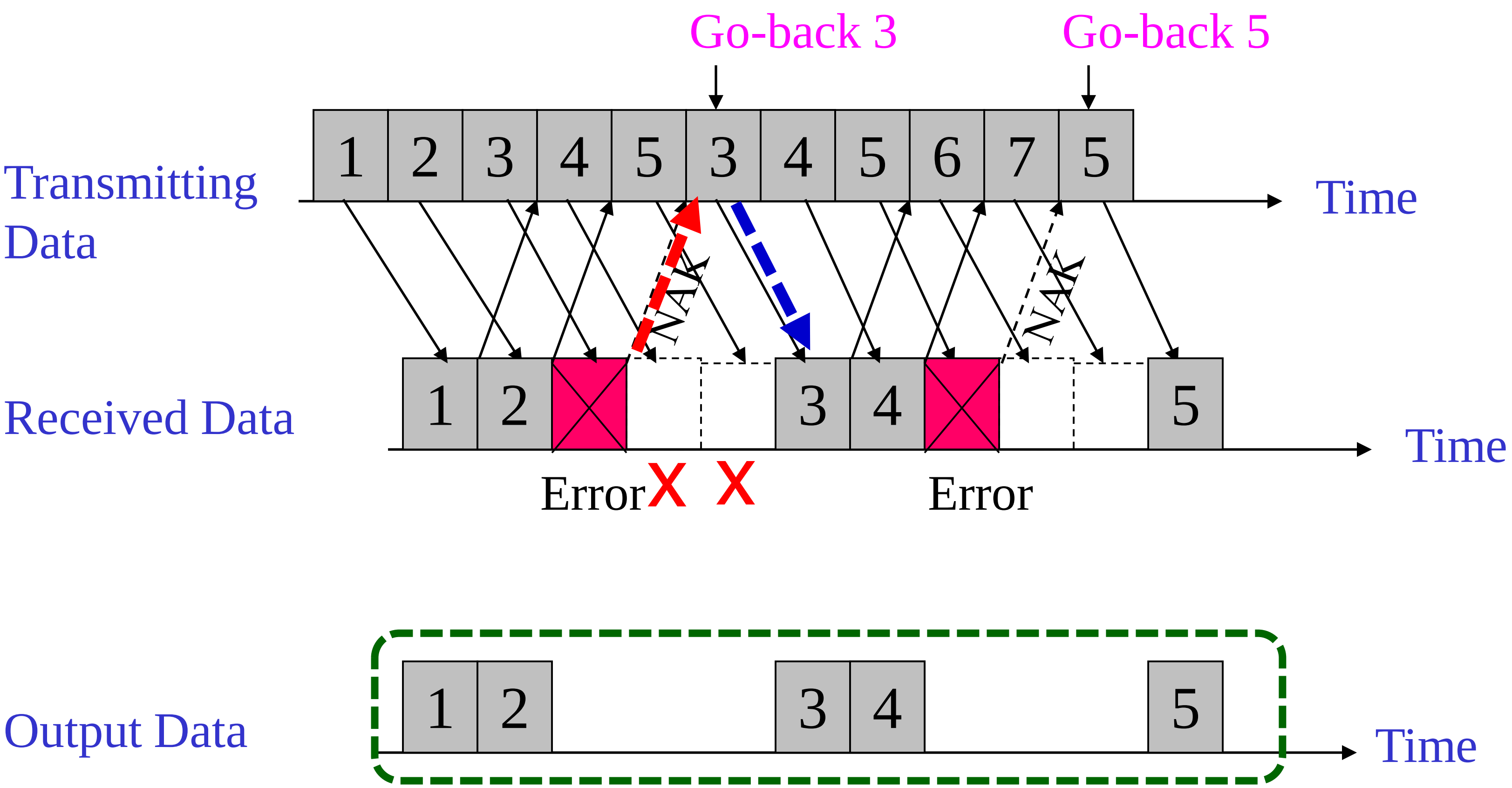
ACK: Acknowledge

NAK: Negative ACK

NAK = NACK

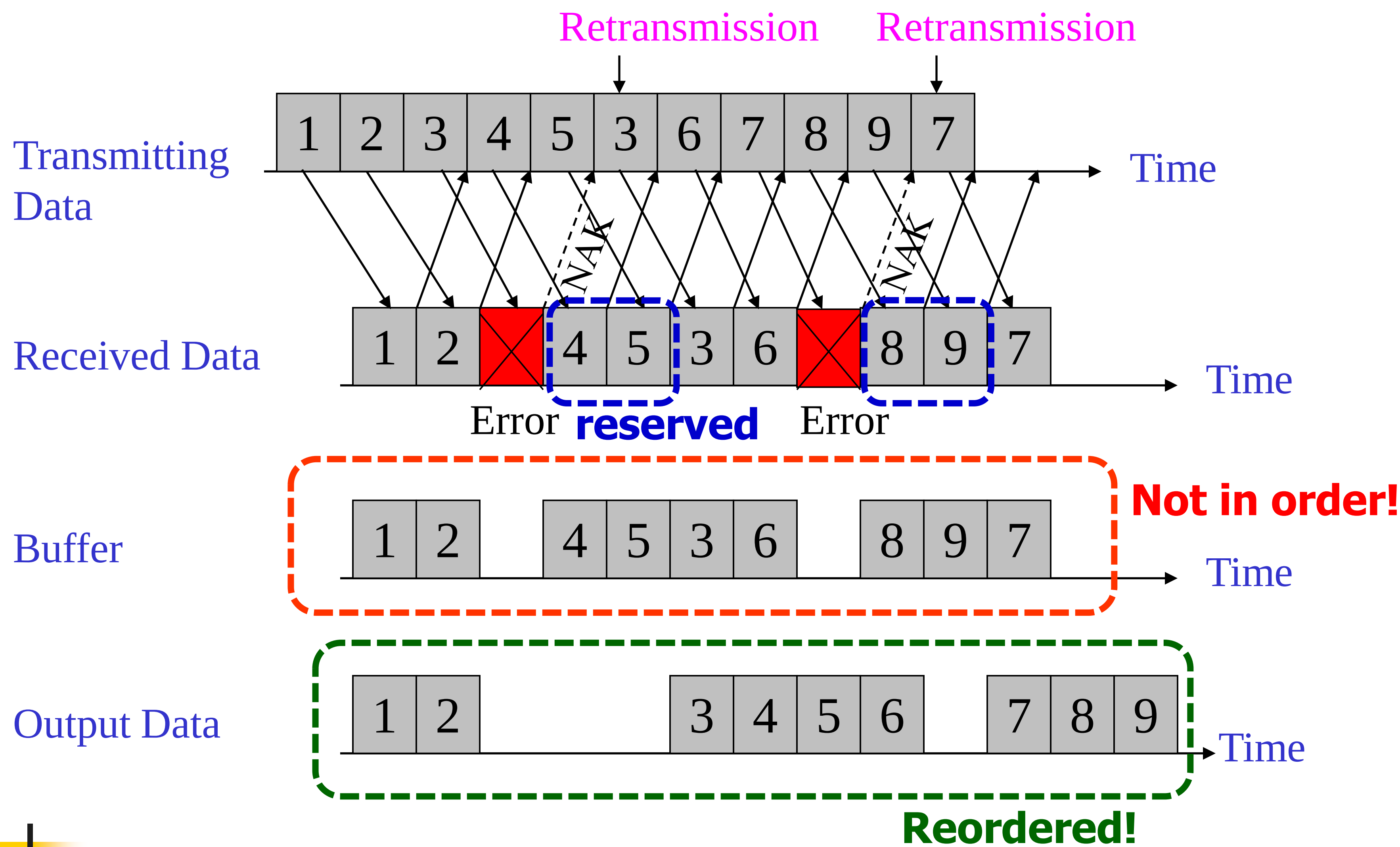
p. 93 (頁105) Fig. 4.12

Go-Back-N ARQ (GBN ARQ)



p. 95 (頁107) Fig. 4.13

Selective-Repeat ARQ (SR ARQ)



p. 96 (頁108) Fig. 4.14

The End of Chapter 4