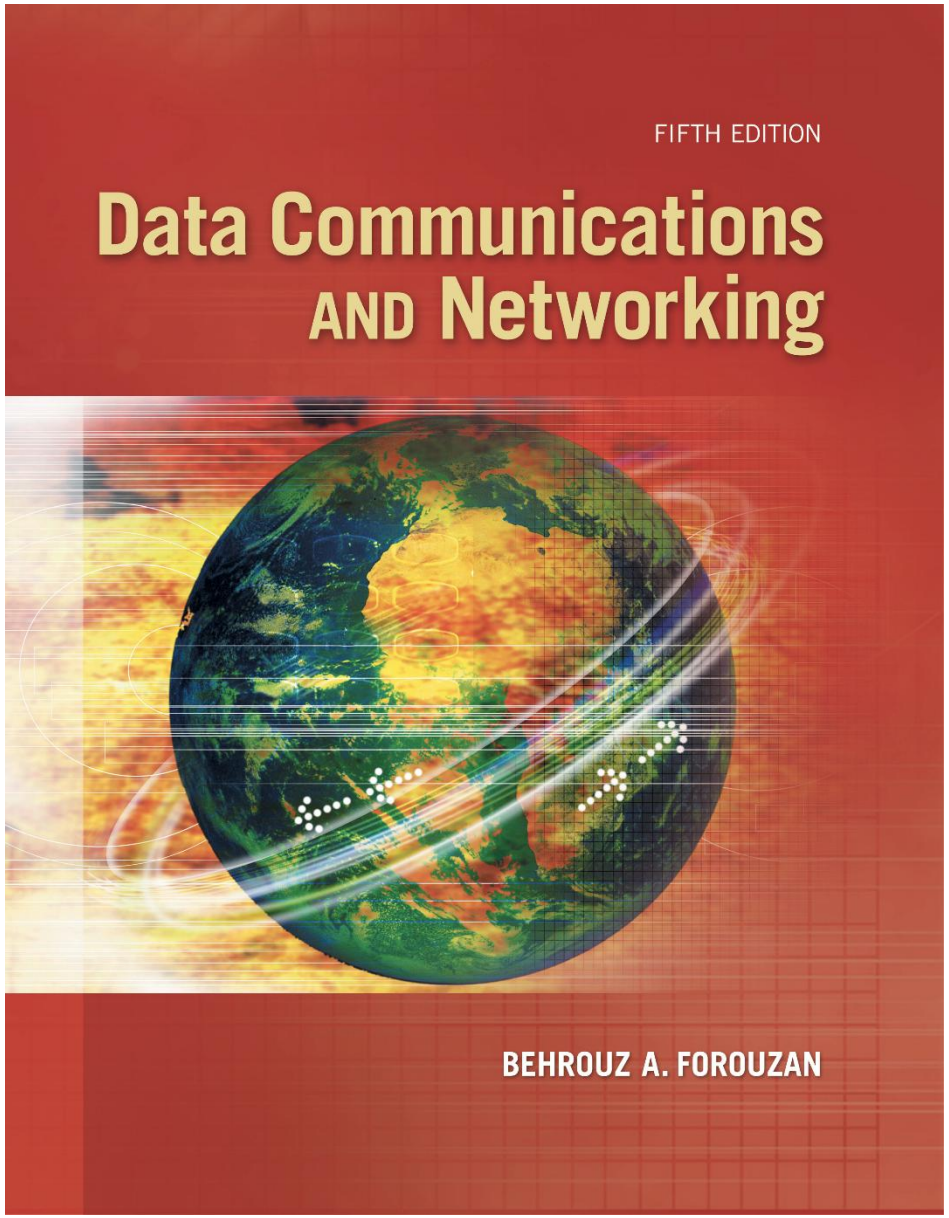
Chapter 11

Data Link Control (DLC)



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Chapter 11: Outline

11.1 DLC SERVICES

11.2 DATA-LINK LAYER PROTOCOLS

11.3 HDLC

11.4 PPP

Chapter 11: Objective

- *The first section discusses the general services provided by the DLC sublayer. It first describes framing and two types of frames used in this sublayer. The section then discusses flow and error control. Finally, the section explains that a DLC protocol can be either connectionless or connection-oriented..*

- *The second section discusses some simple and common data-link protocols that are implemented at the DLC sublayer. The section first describes the Simple Protocol. It then explains the Stop-and-Wait Protocol.*

Chapter 11: Objective (continued)

- *The third section introduces HDLC, a protocol that is the basis of all common data-link protocols in use today such as PPP and Ethernet. The section first talks about configurations and transfer modes. It then describes framing and three different frame formats used in this protocol.*

- *The fourth section discusses PPP, a very common protocol for point-to-point access. It first introduces the services provided by the protocol. The section also describes the format of the frame in this protocol. It then describes the transition mode in the protocol using an FSM. The section finally explains multiplexing in PPP.*

11-1 DLC SERVICES

The data link control (DLC) deals with procedures for communication between two adjacent nodes no matter whether the link is dedicated or broadcast. Data link control functions include framing and flow and error control. In this section, we first discuss framing, or how to organize the bits that are carried by the physical layer. We then discuss flow and error control.

11.1.1 Framing

The data-link layer needs to pack bits into frames, so that each frame is distinguishable from another. Our postal system practices a type of framing. The simple act of inserting a letter into an envelope separates one piece of information from another; the envelope serves as the delimiter.

Framing in the data-link layer separates a message from one source to a destination by adding a sender address and a destination address. The destination address defines where the packet is to go; the sender address helps the recipient acknowledge the receipt.

Frame size

- Larger frames are more vulnerable to errors
- Frames can be fixed-size or variable-size
  - E.g. ATM : 53 bytes packet
- Variable size framing
  - Character-oriented
  - Bit-oriented

Figure 11.1: A frame in a character-oriented protocol

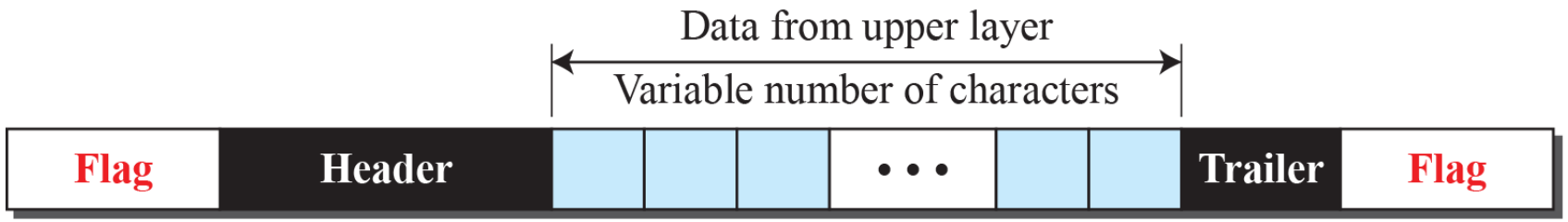


Figure 11.2: Byte stuffing and unstuffing

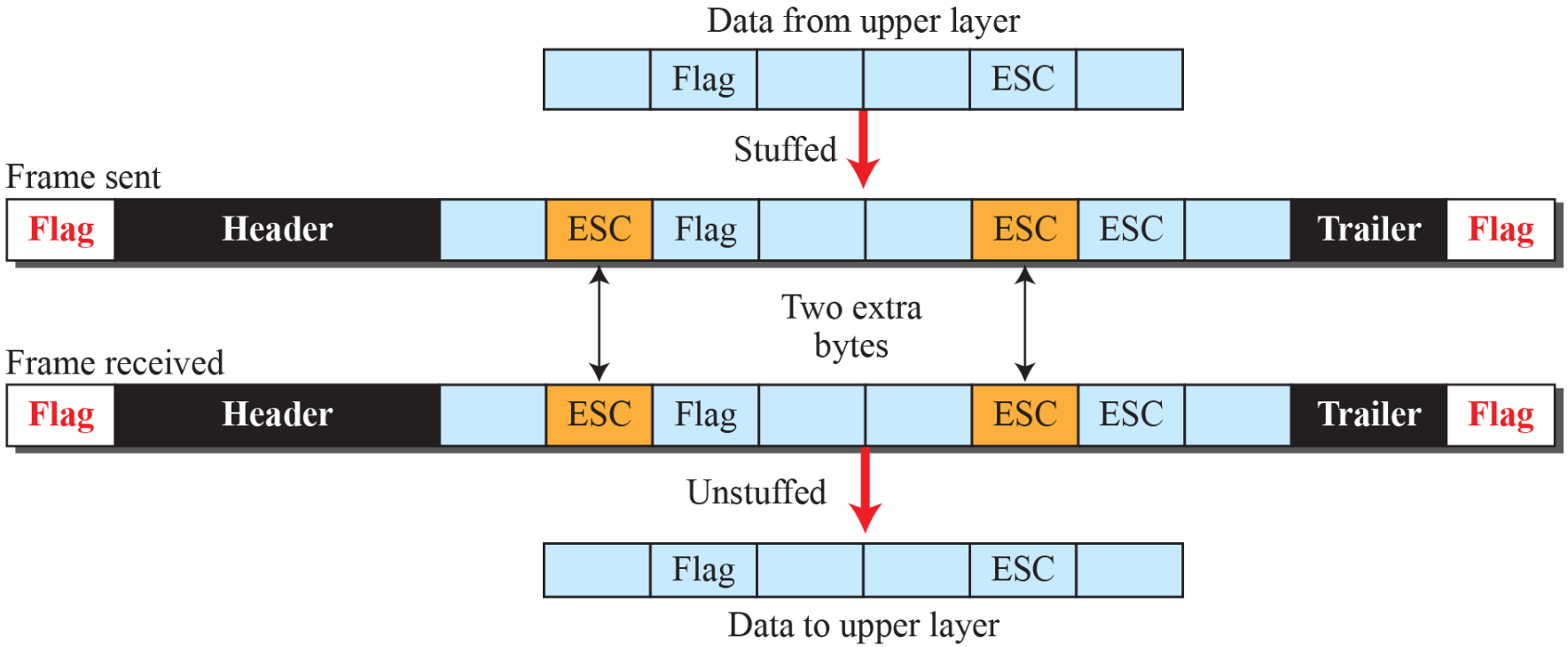


Figure 11.3: A frame in a bit-oriented protocol

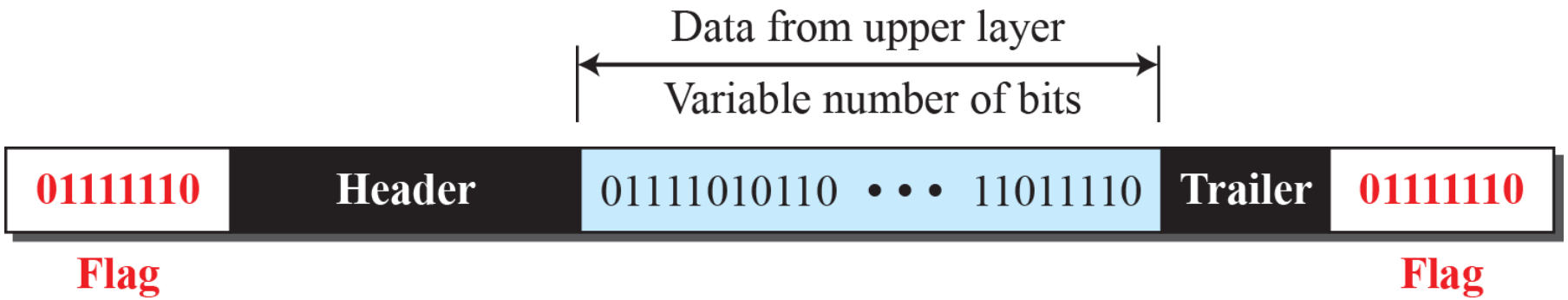
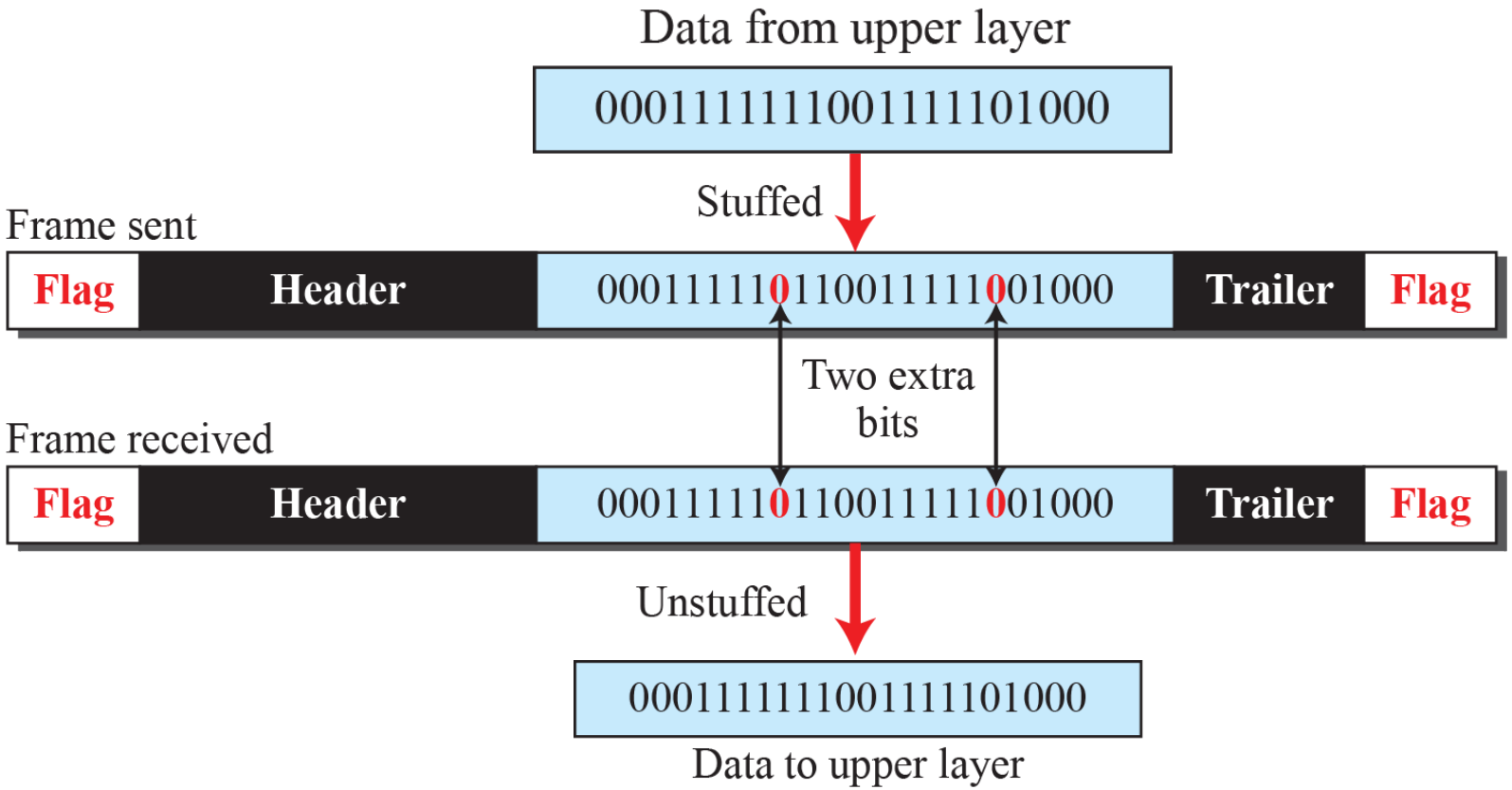


Figure 11.4: Bit stuffing and unstuffing

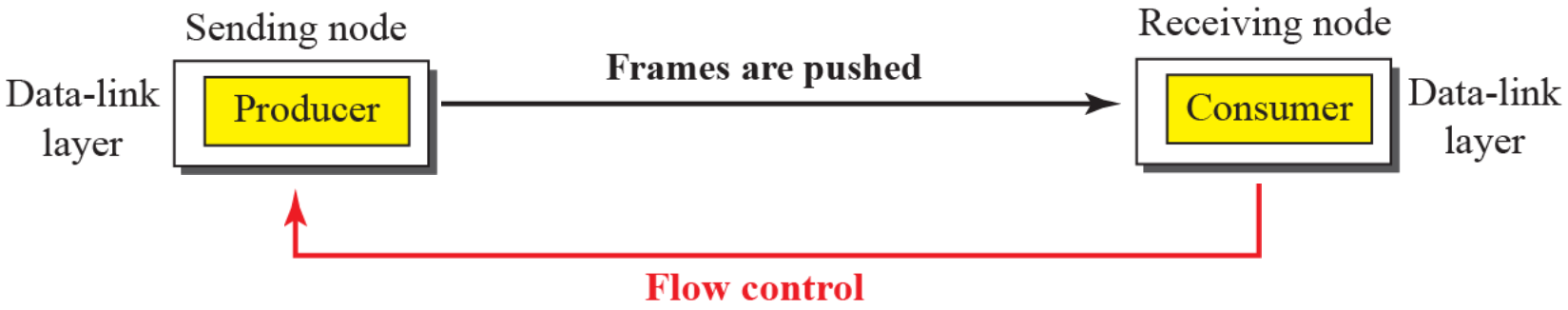
Add one extra 0 whenever five consecutive 1's follow 0



11.1.2 Flow and Error Control

We briefly defined flow and error control in Chapter 9; we elaborate on these two issues here. One of the responsibilities of the data-link control sublayer is flow and error control at the data-link layer.

Figure 11.5: Flow control at the data link layer



Example 11.1

The above discussion requires that the consumers communicate with the producers on two occasions: when the buffer is full and when there are vacancies. If the two parties use a buffer with only one slot, the communication can be easier. Assume that each data-link layer uses one single memory slot to hold a frame. When this single slot in the receiving data-link layer is empty, it sends a note to the network layer to send the next frame.

Error control

- [Positive] ACK

- Negative ACK (NACK)

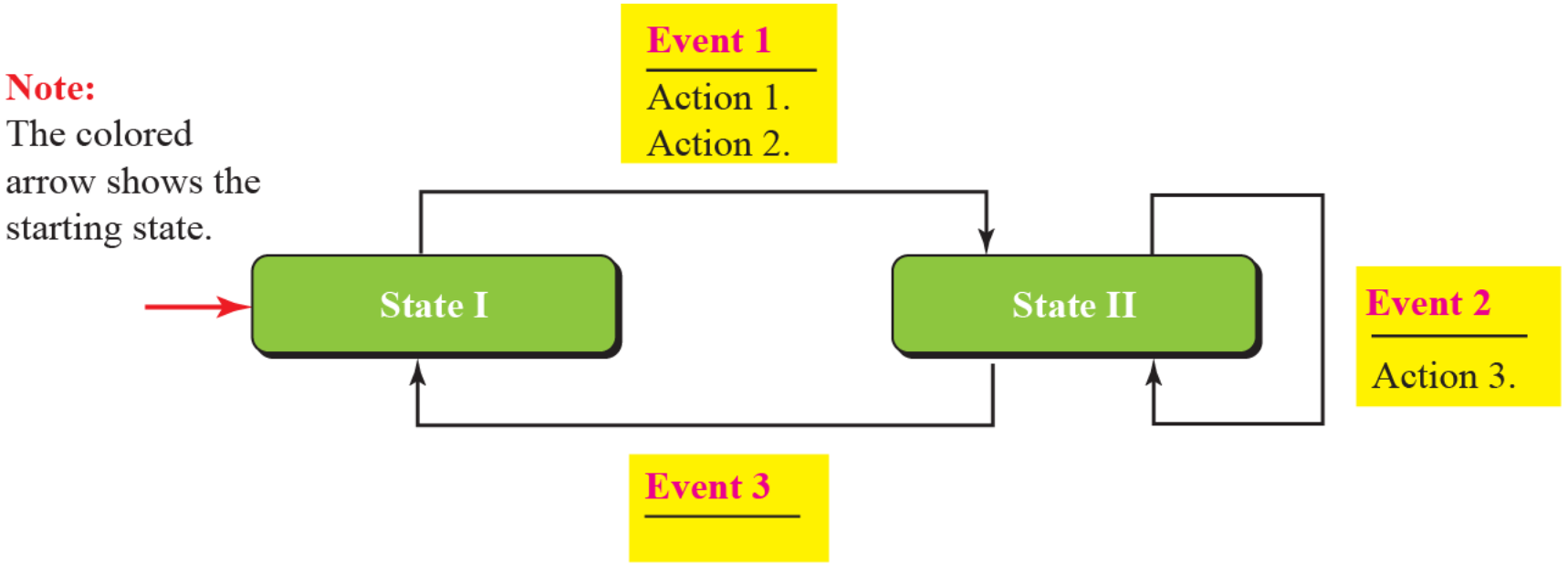
11.1.3 Connection

A DLC protocol can be either connectionless or connection-oriented. We will discuss this issue very briefly here, but we return to this topic in the network and transport layer.

11-2 DATA-LINK LAYER PROTOCOLS

Traditionally four protocols have been defined for the data-link layer to deal with flow and error control: Simple, Stop-and-Wait, Go-Back-N, and Selective-Repeat. Although the first two protocols still are used at the data-link layer, the last two have disappeared. We therefore briefly discuss the first two protocols in this chapter.

Figure 11.6: FSMs



11.2.1 Simple Protocol

Our first protocol is a simple protocol with neither flow nor error control. We assume that the receiver can immediately handle any frame it receives. In other words, the receiver can never be overwhelmed with incoming frames. Figure 11.7 shows the layout for this protocol.

Figure 11.7: Simple protocol

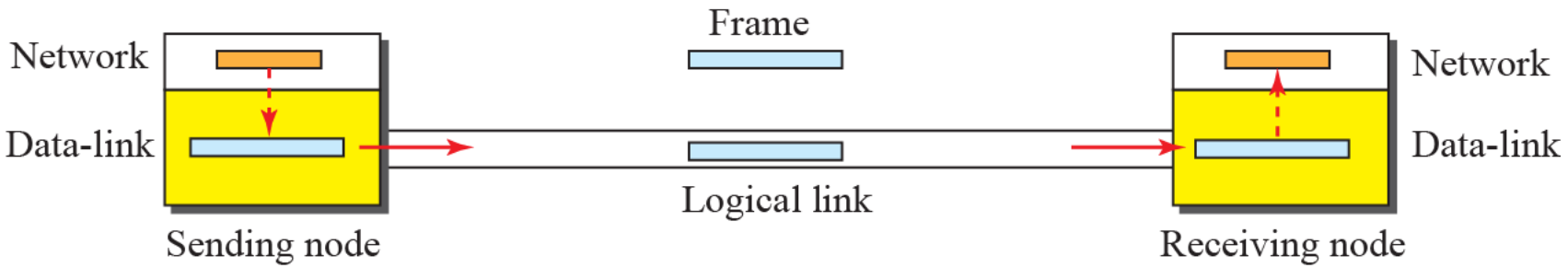
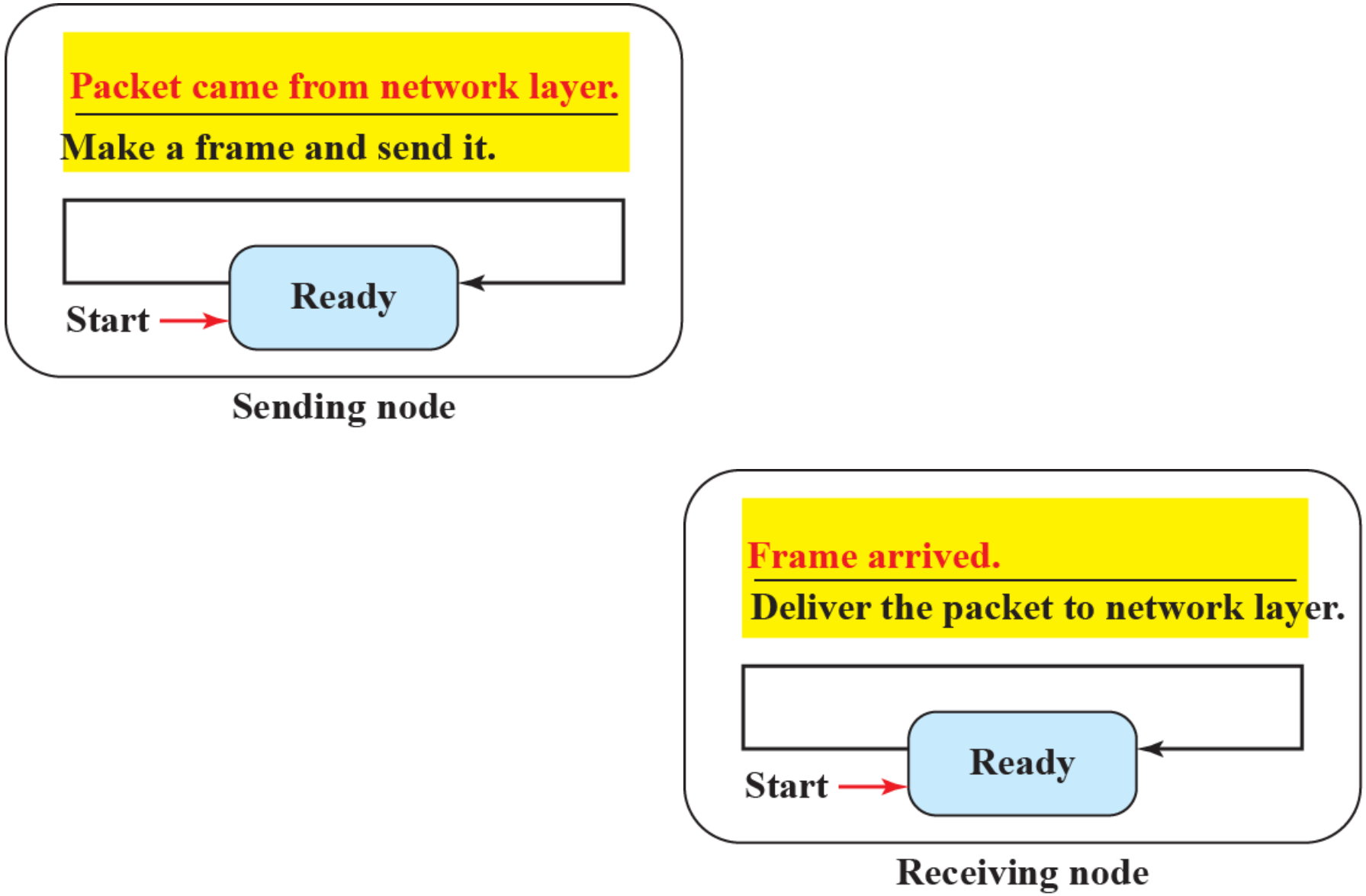


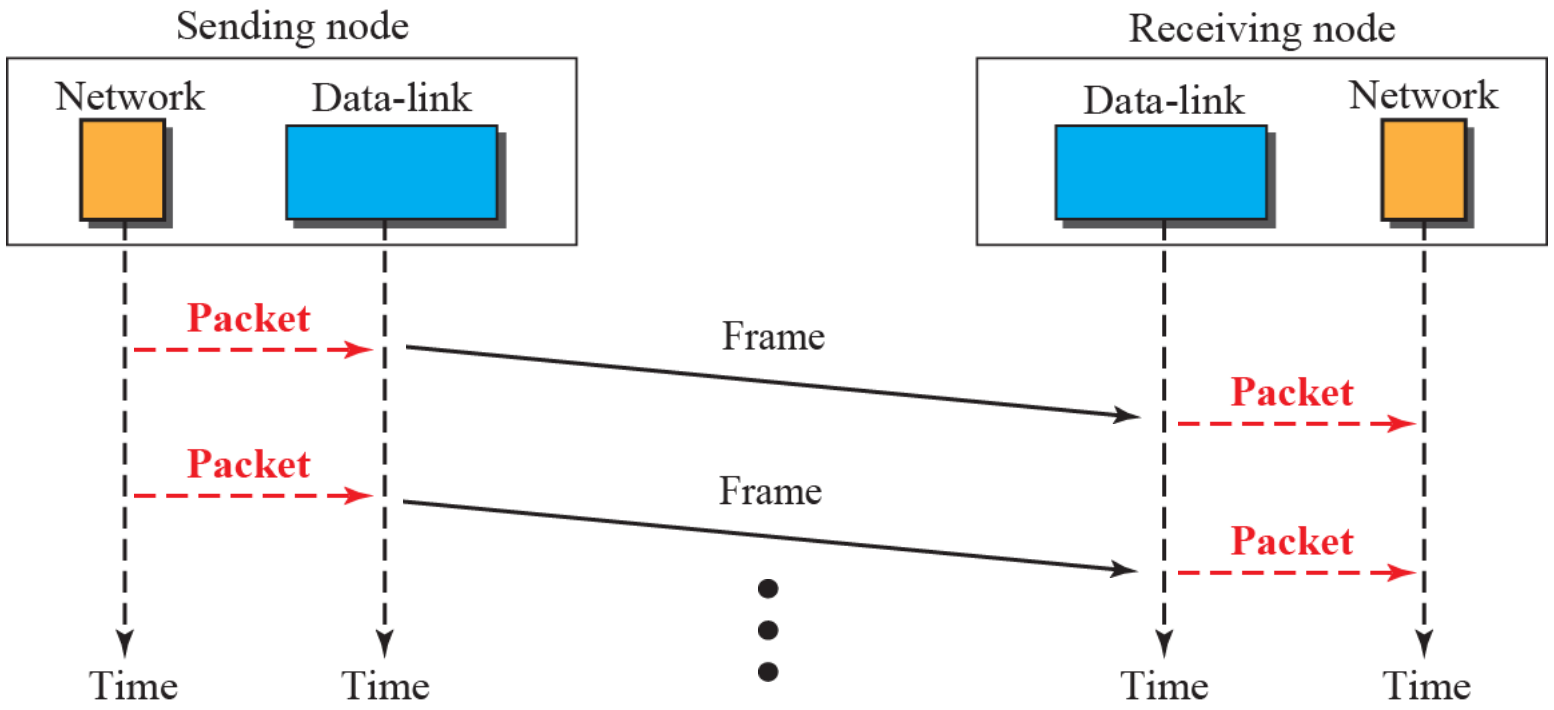
Figure 11.8: FSM for the simple protocol



Example 11.2

Figure 11.9 shows an example of communication using this protocol. It is very simple. The sender sends frames one after another without even thinking about the receiver.

Figure 11.9: Flow diagram for Example 11.2



11.2.2 Stop-and-Wait Protocol

Our second protocol is called the Stop-and-Wait protocol, which uses both flow and error control. We show a primitive version of this protocol here, but we discuss the more sophisticated version in Chapter 23 when we have learned about sliding windows. In this protocol, the sender sends one frame at a time and waits for an acknowledgment before sending the next one. To detect corrupted frames, we need to add a CRC (see Chapter 10) to each data frame.

Figure 11.10: Stop-and-wait Protocol

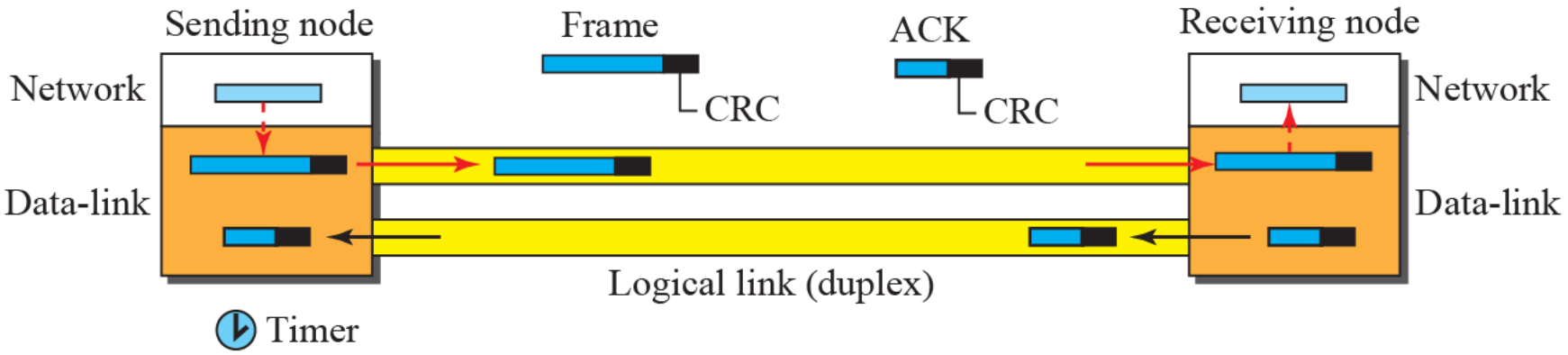
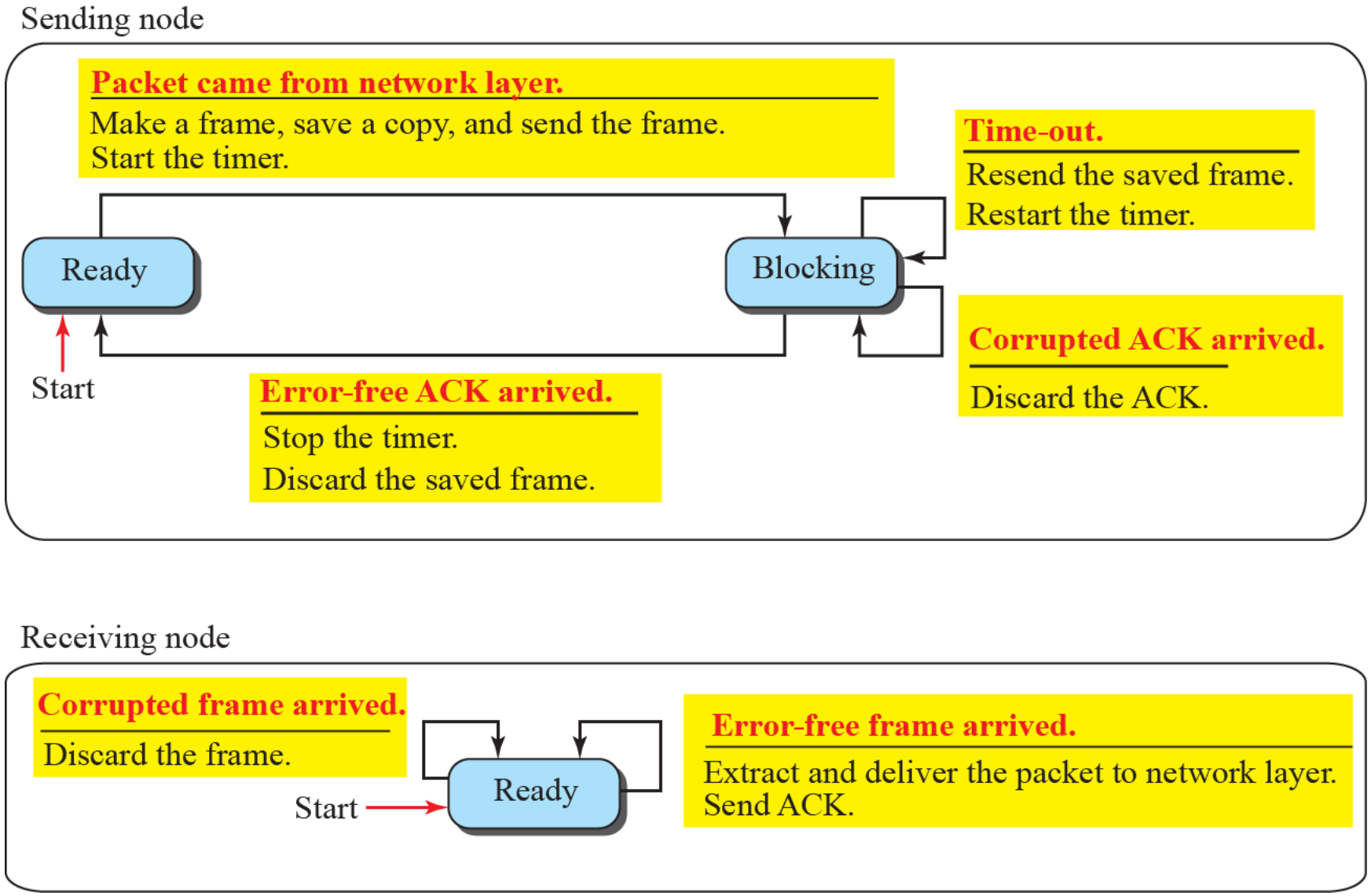


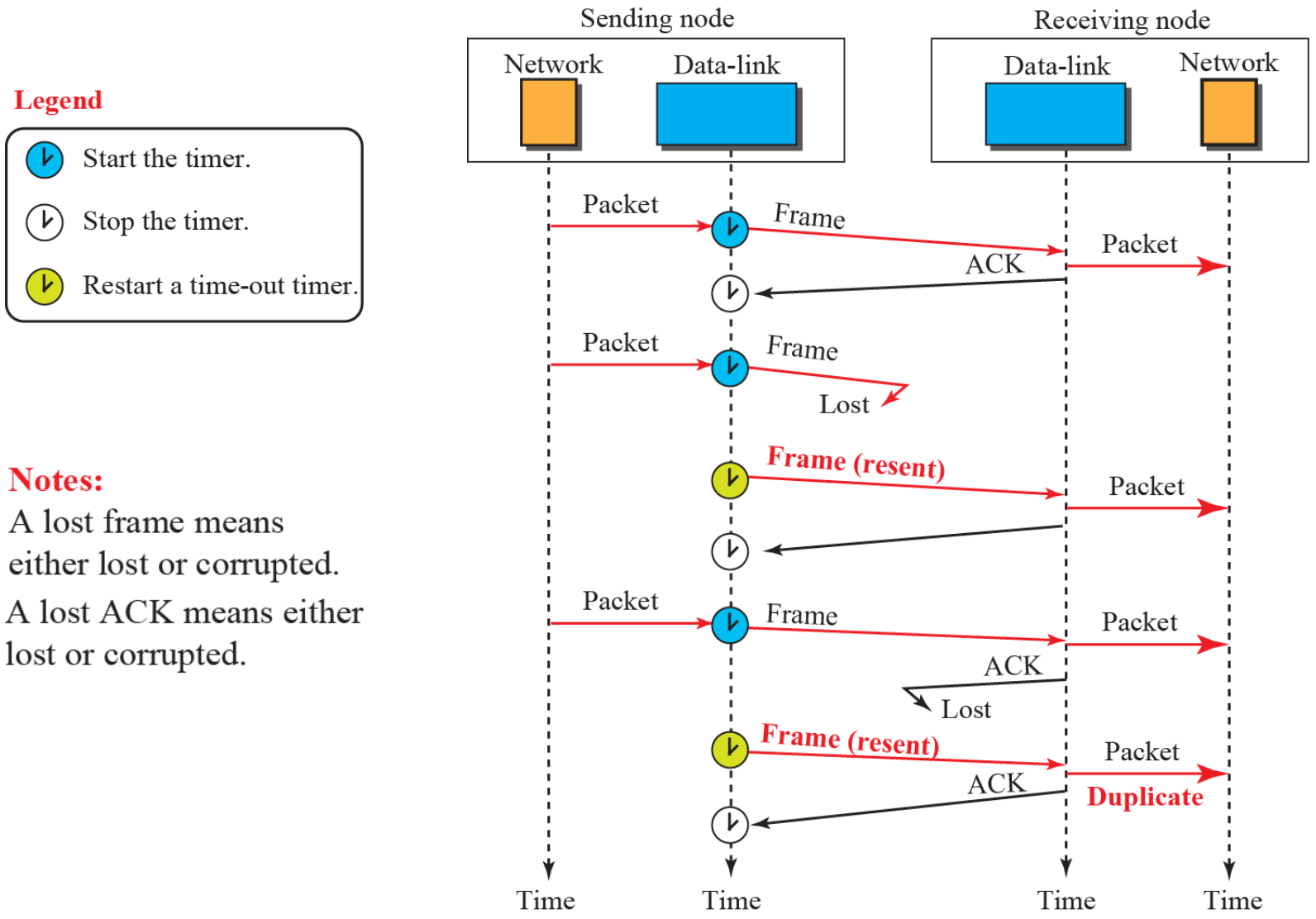
Figure 11.11: FSM for the stop-and-wait protocol



Example 11.3

Figure 11.12 shows an example. The first frame is sent and acknowledged. The second frame is sent, but lost. After time-out, it is resent. The third frame is sent and acknowledged, but the acknowledgment is lost. The frame is resent. However, there is a problem with this scheme. The network layer at the receiver site receives two copies of the third packet, which is not right. In the next section, we will see how we can correct this problem using sequence numbers and acknowledgment numbers.

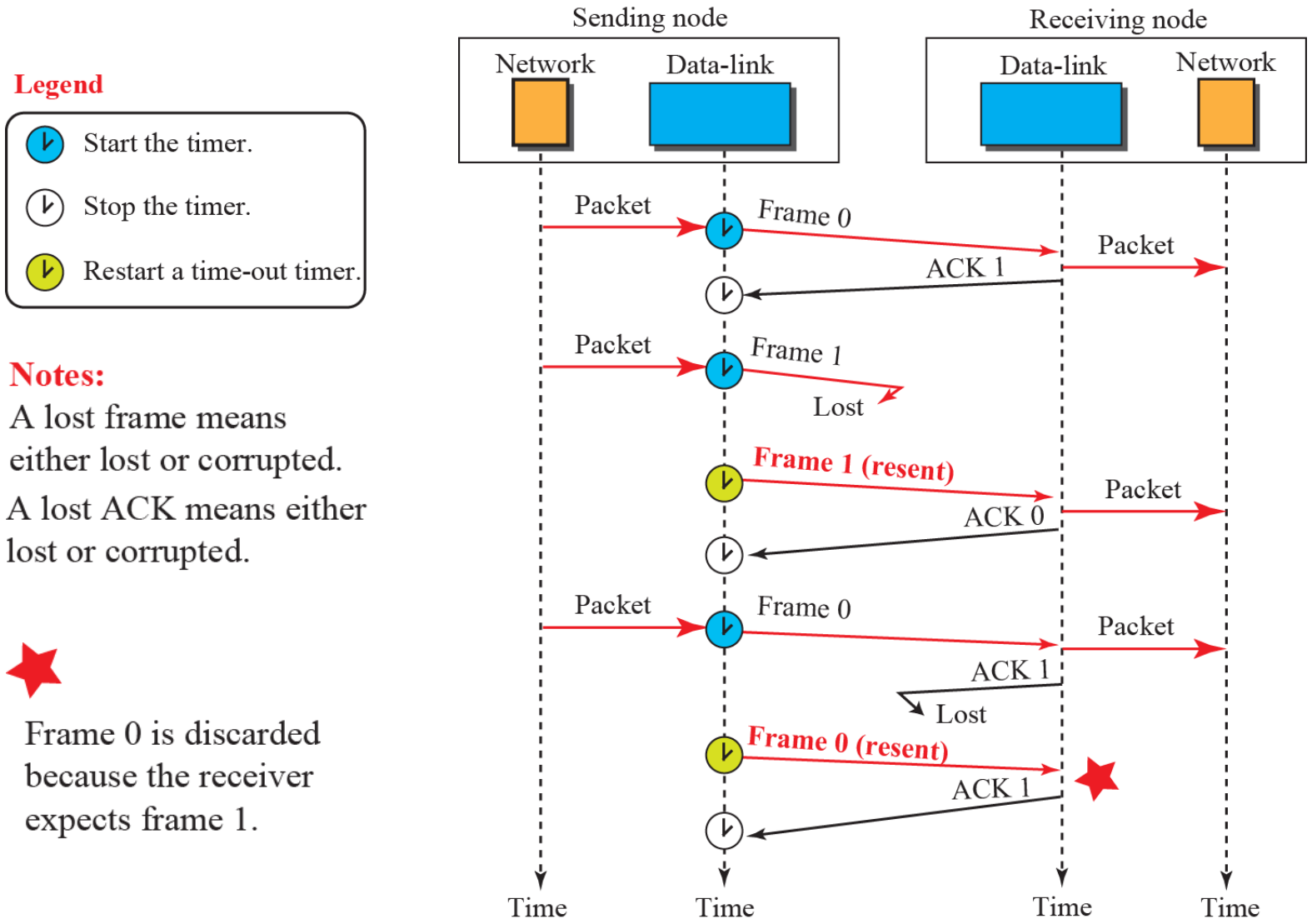
Figure 11.12: Flow diagram for Example 11.3



Example 11.4

Figure 11.13 shows how adding sequence numbers and acknowledgment numbers can prevent duplicates. The first frame is sent and acknowledged. The second frame is sent, but lost. After time-out, it is resent. The third frame is sent and acknowledged, but the acknowledgment is lost. The frame is resent.

Figure 11.13: Flow diagram for Example 11.4



11.2.3 Piggybacking

The two protocols we discussed in this section are designed for unidirectional communication, in which data is flowing only in one direction although the acknowledgment may travel in the other direction. Protocols have been designed in the past to allow data to flow in both directions. However, to make the communication more efficient, the data in one direction is piggybacked with the acknowledgment in the other direction.

11-3 HDLC

High-level Data Link Control (HDLC) is a bit - oriented protocol for communication over point-to-point and multipoint links. It implements the Stop-and-Wait protocol we discussed earlier. Although this protocol is more a theoretical issue than practical, most of the concept defined in this protocol is the basis for other practical protocols such as PPP, Ethernet, or wireless LANs.

11.3.1 Transfer Modes

HDLC provides two common transfer modes that can be used in different configurations: normal response mode (NRM) and asynchronous balanced mode (ABM).

Figure 11.14: Normal response mode

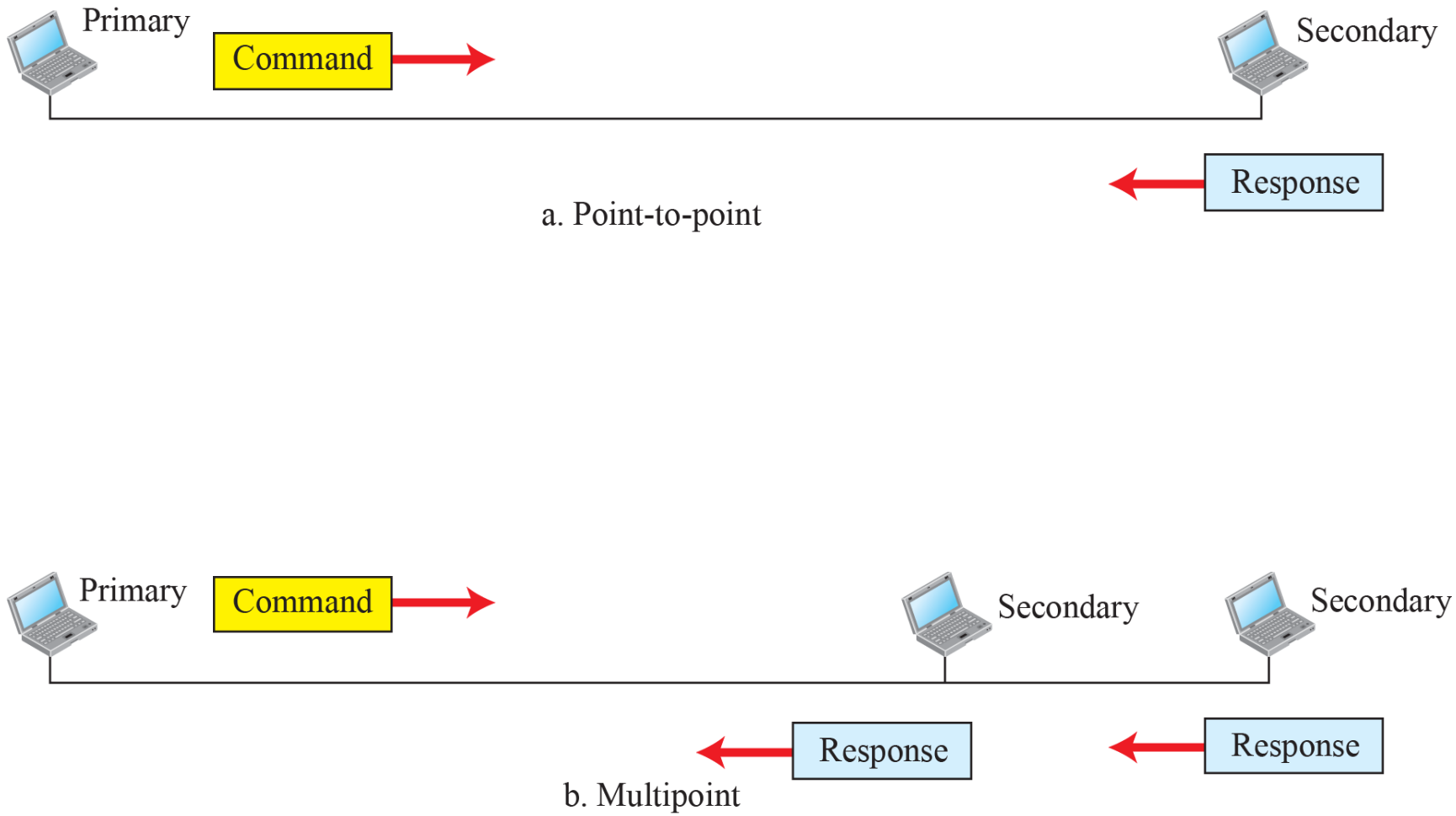


Figure 11.15: Asynchronous balanced mode



11.3.2 Framing

To provide the flexibility necessary to support all the options possible in the modes and configurations just described, HDLC defines three types of frames: information frames (I-frames), supervisory frames (S-frames), and unnumbered frames (U-frames).

Figure 11.16: HDLC frames

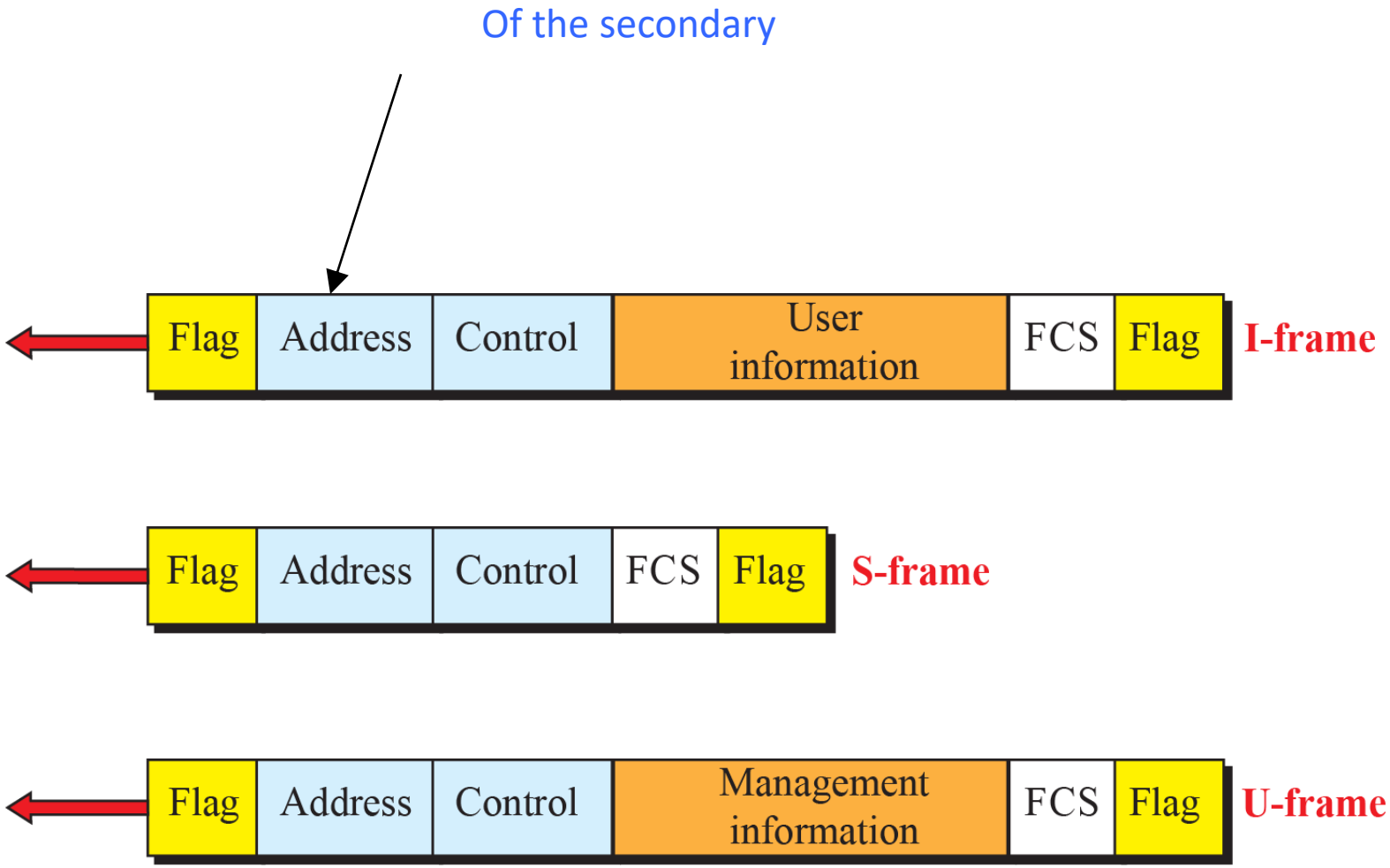
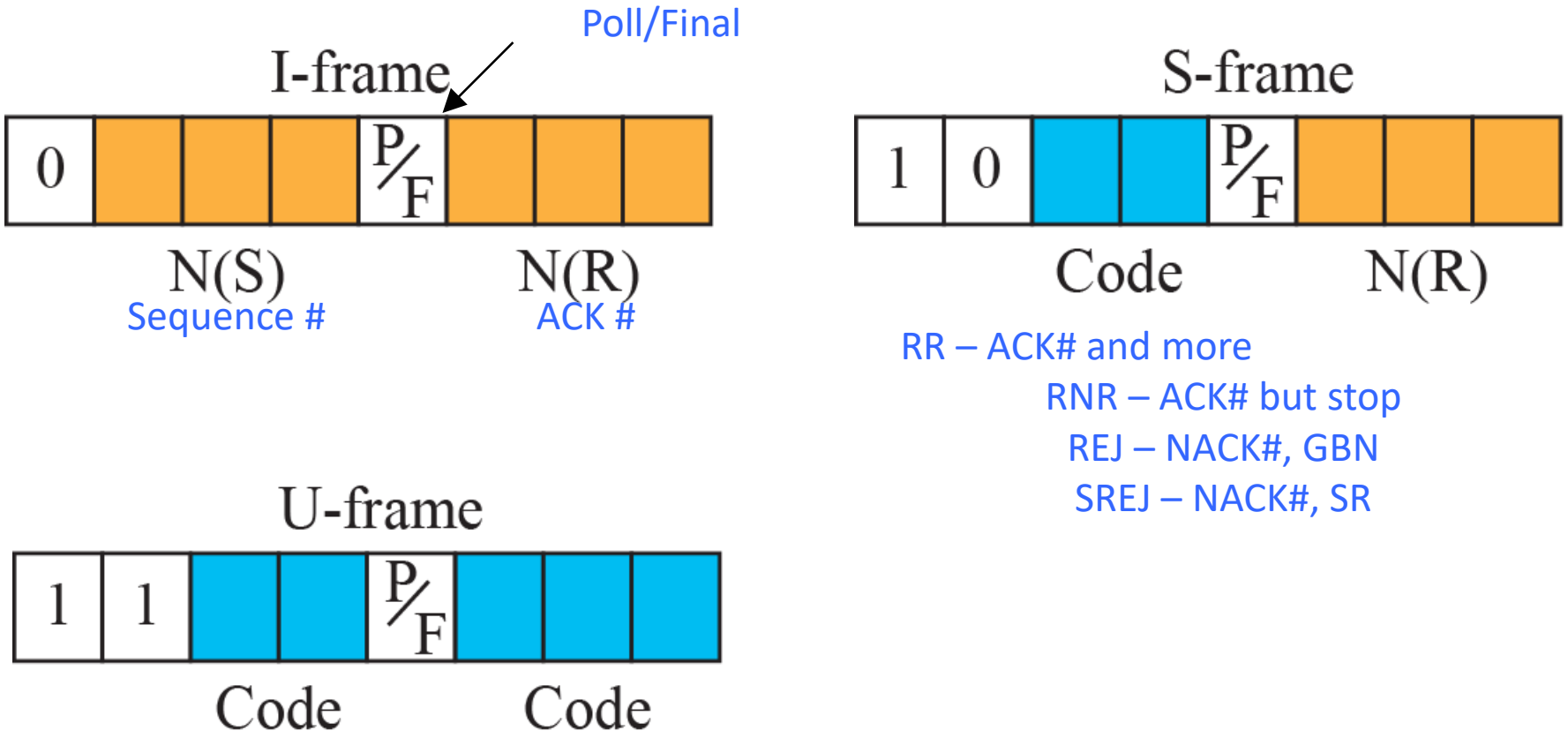


Figure 11.17: Control field format for the different frame types

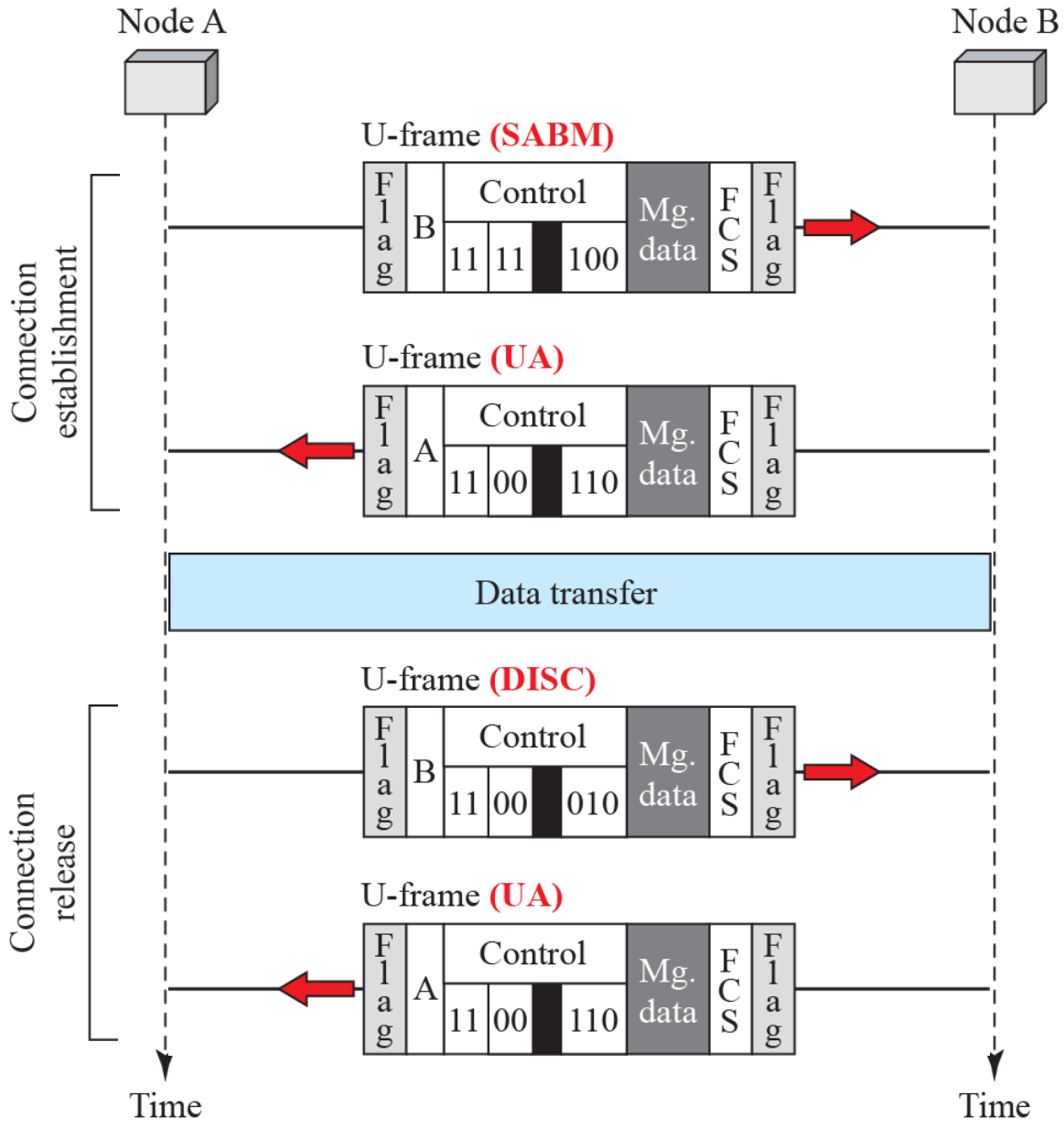
For flow and error control



Example 11.5

Figure 11.18 shows how U-frames can be used for connection establishment and connection release. Node A asks for a connection with a set asynchronous balanced mode (SABM) frame; node B gives a positive response with an unnumbered acknowledgment (UA) frame. After these two exchanges, data can be transferred between the two nodes (not shown in the figure). After data transfer, node A sends a DISC (disconnect) frame to release the connection; it is confirmed by node B responding with a UA (unnumbered acknowledgment).

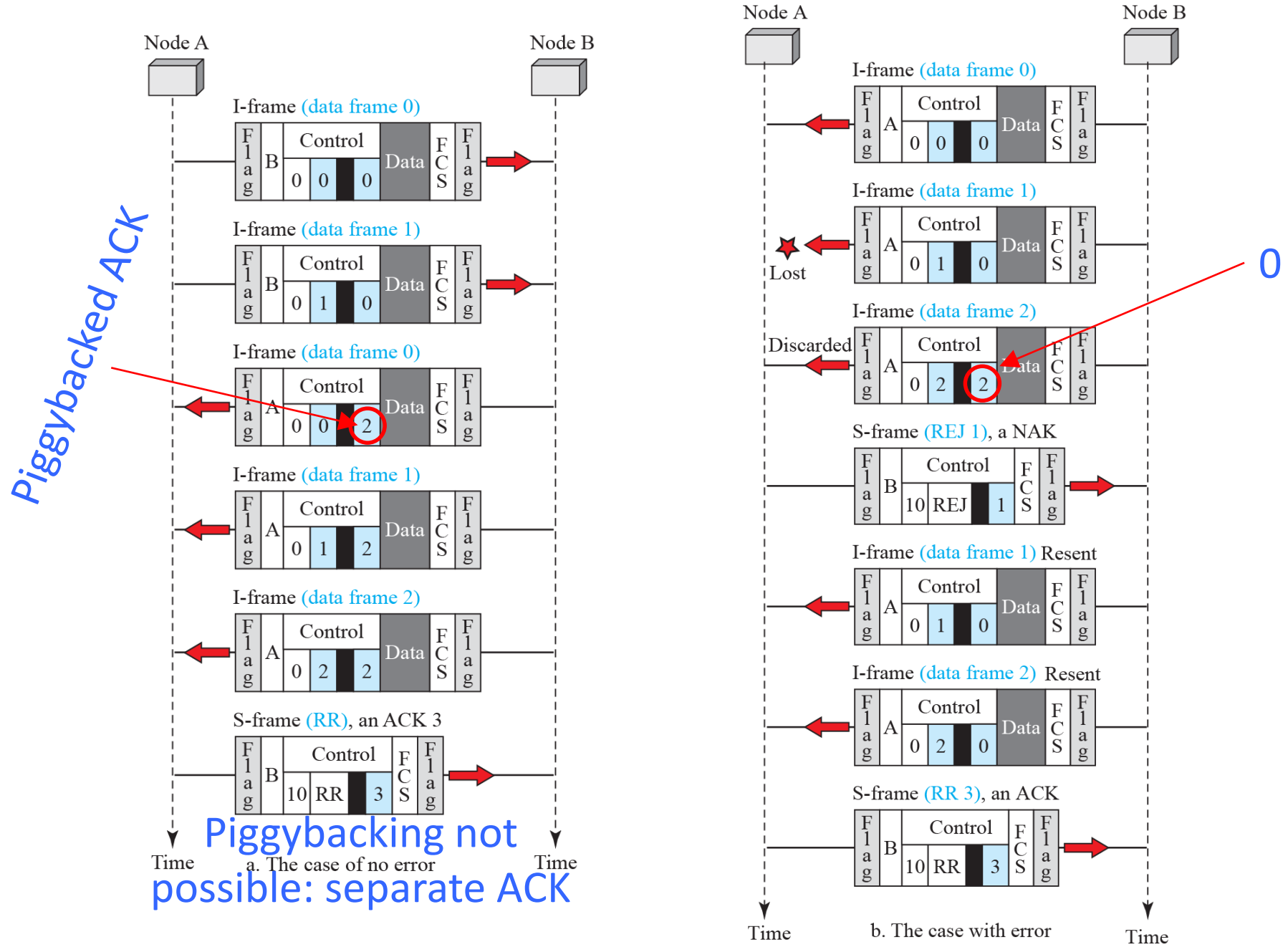
Figure 11.18: Example of connection and disconnection



Example 11.6

Figure 11.19 shows two exchanges using piggybacking. The first is the case where no error has occurred; the second is the case where an error has occurred and some frames are discarded.

Figure 11.19: Example of piggybacking with and without error



11-4 PPP

One of the most common protocols for point-to-point access is the Point-to-Point Protocol (PPP). Today, millions of Internet users who need to connect their home computers to the server of an Internet service provider use PPP. To control and manage the transfer of data, there is a need for a point-to-point protocol at the data-link layer. PPP is by far the most common.

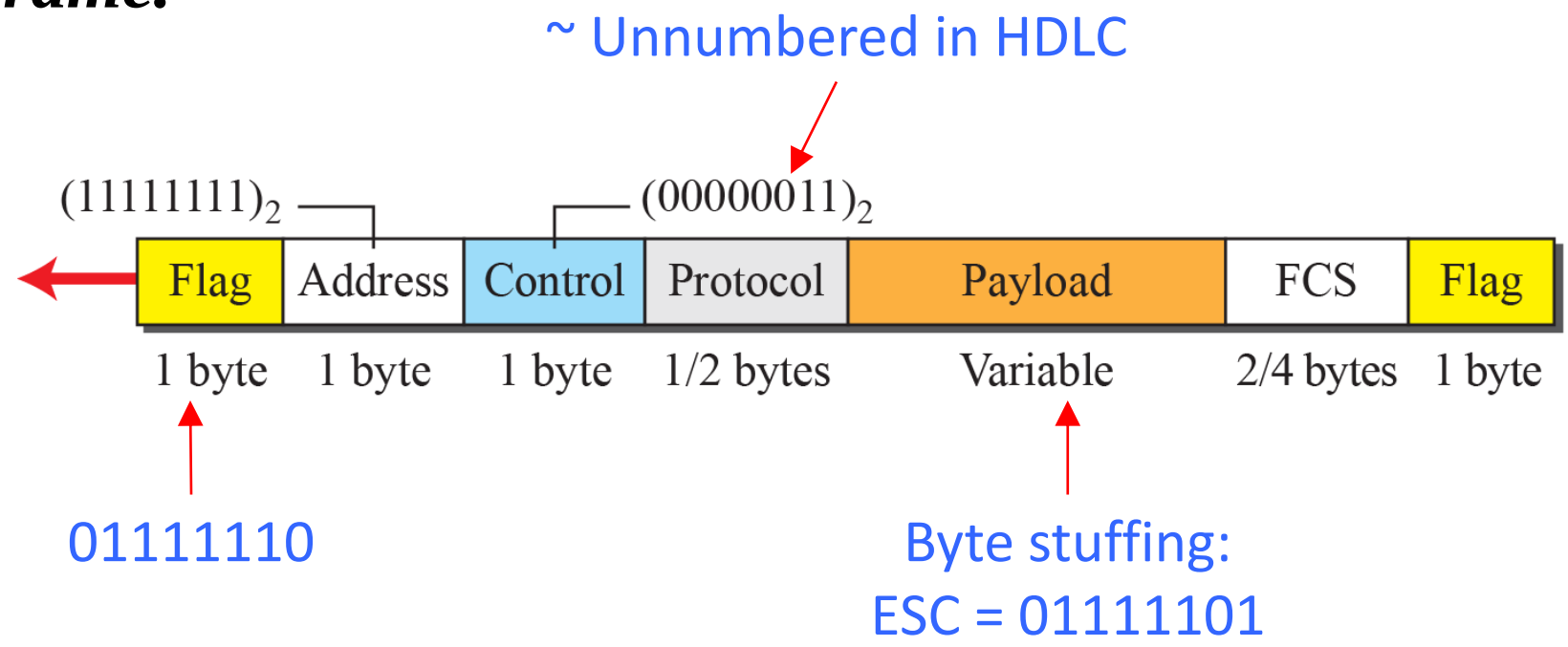
11.4.1 Services

The designers of PPP have included several services to make it suitable for a point-to-point protocol, but have ignored some traditional services to make it simple.

No flow control

11.4.2 Framing

PPP uses a character-oriented (or byte-oriented) frame. Figure 11.20 shows the format of a PPP frame.

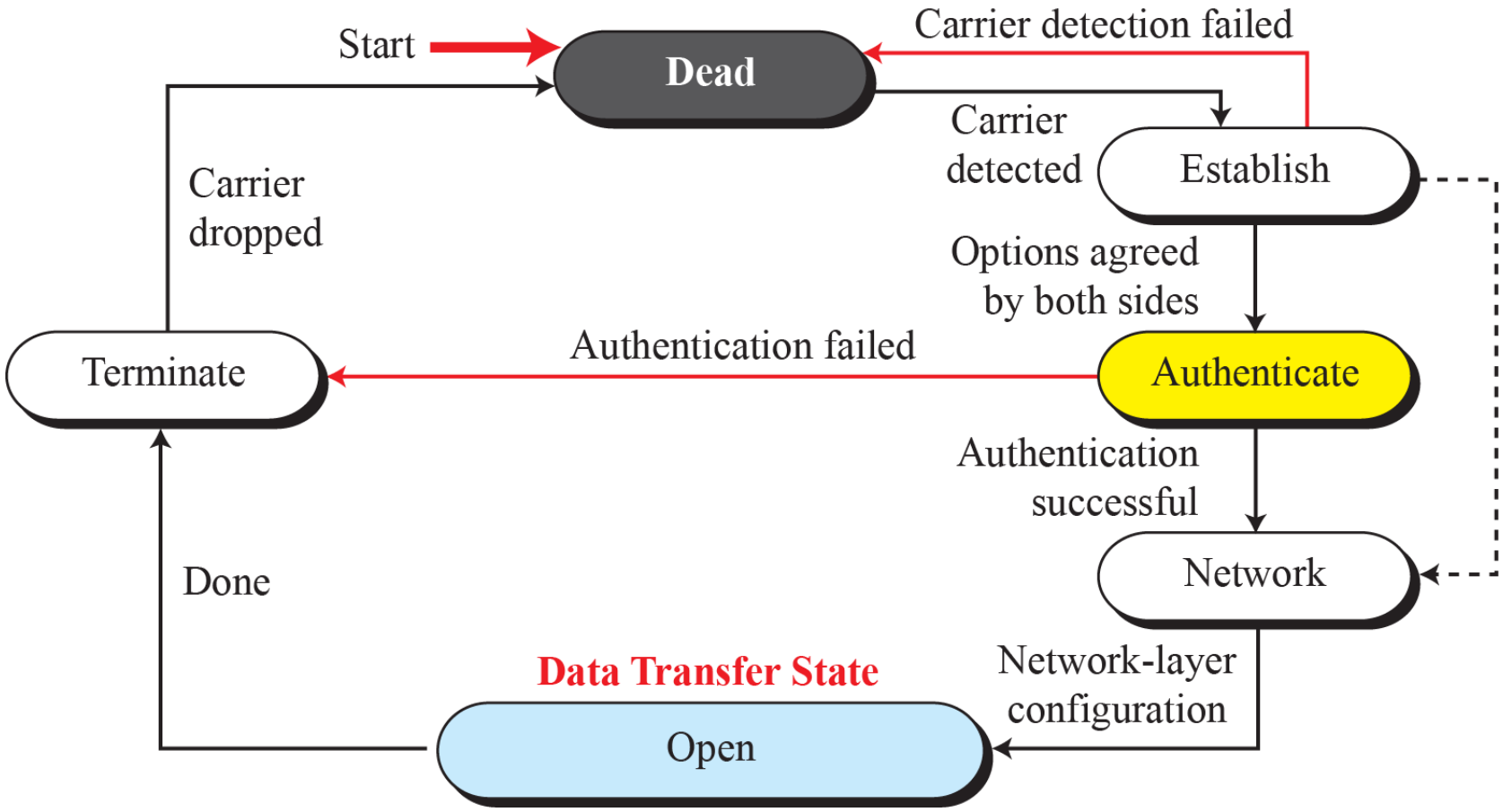


11.4.3 Transition Phases

A PPP connection goes through phases which can be shown in a transition phase diagram.

- Dead: line is quiet
- Establish: options are negotiated through link-control protocol packets
  - E.g. authentication
- Open: data exchange takes place
- Terminate: wait until the carrier is dropped, which brings us back to the Dead state

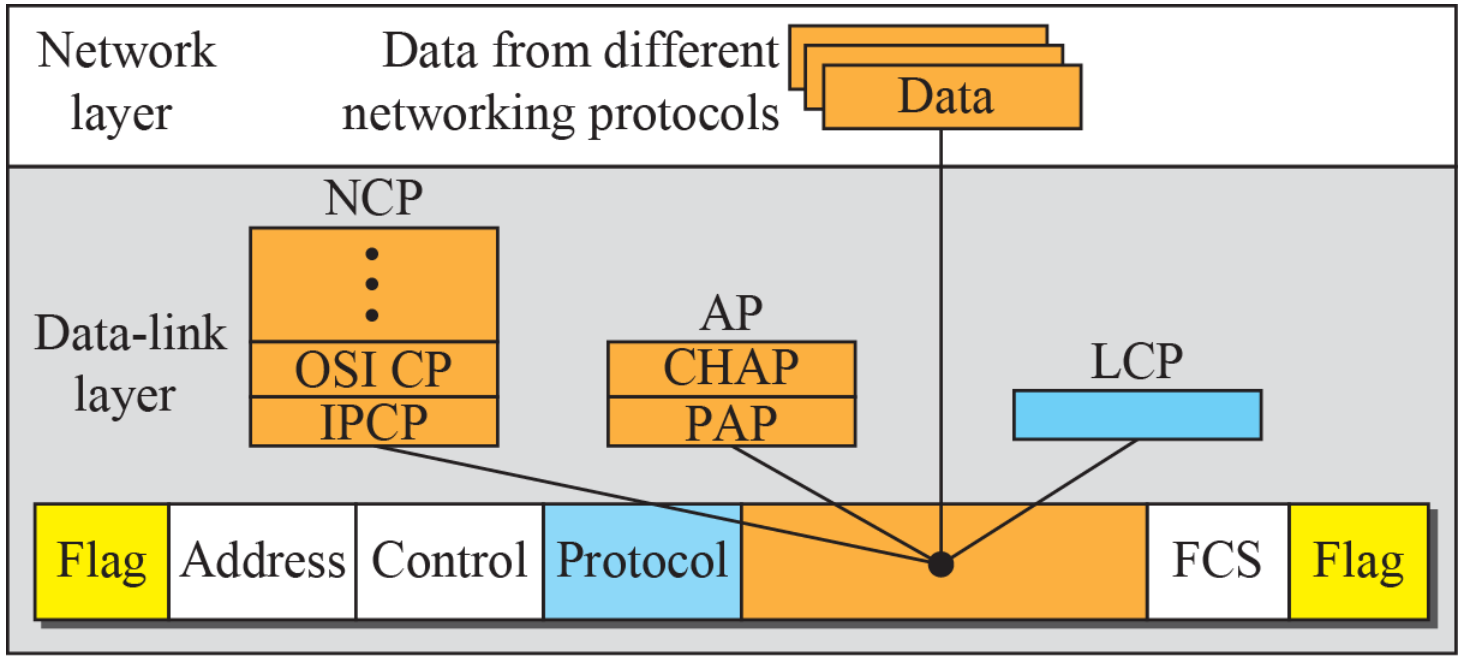
Figure 11.21: Transition phases



11.4.4 Multiplexing

Although PPP is a link-layer protocol, it uses another set of protocols to establish the link, authenticate the parties involved, and carry the network-layer data. Three sets of protocols are defined to make PPP powerful: the Link Control Protocol (LCP), two Authentication Protocols (APs), and several Network Control Protocols (NCPs).

Figure 11.22: Multiplexing in PPP



Legend

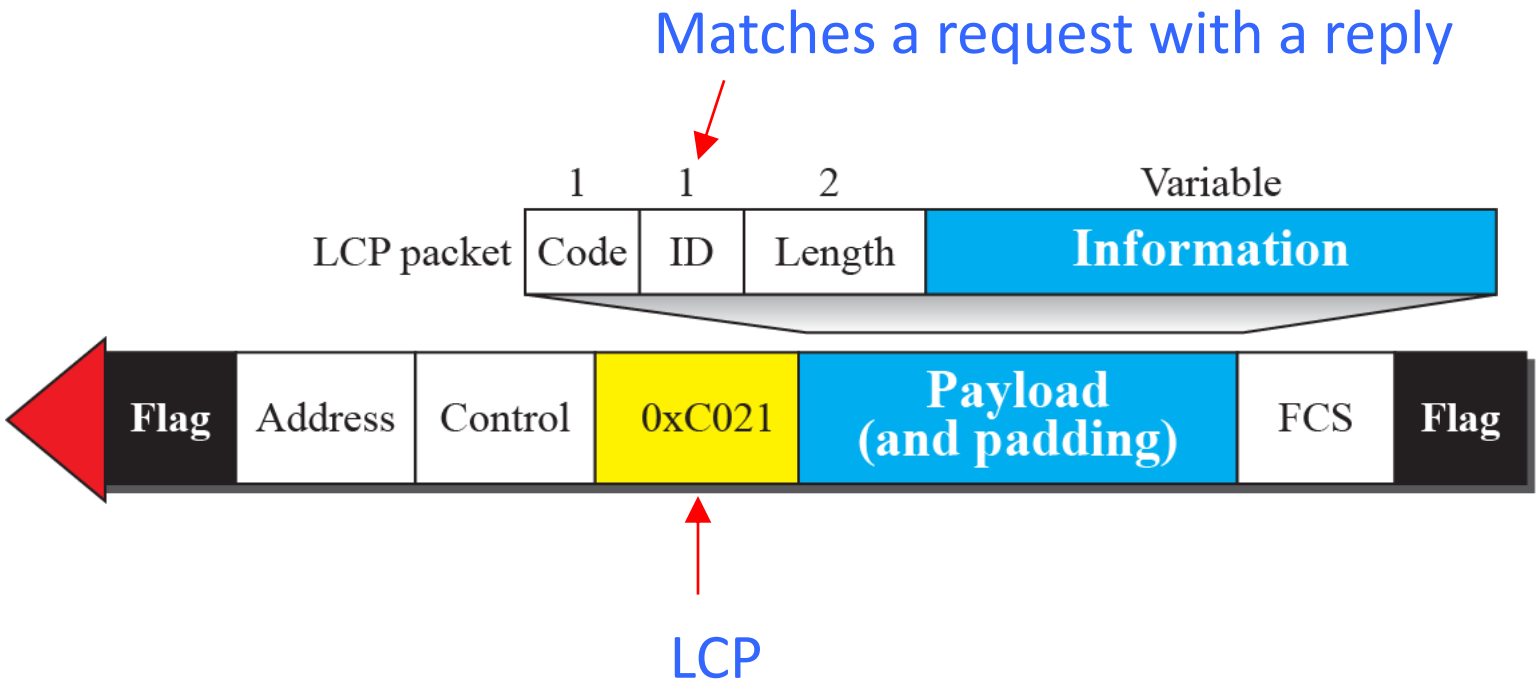
LCP : Link control protocol
AP : Authentication protocol
NCP: Network control protocol

Protocol values:

LCP : 0xC021
AP : 0xC023 and 0xC223
NCP: 0x8021 and ....
Data: 0x0021 and ....

Figure 11.23: LCP packet encapsulated in a frame

- Establish, maintain, configure, and terminate links
- Negotiates mechanisms to set options between two endpoints



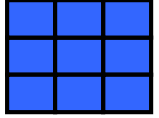


Table 11.1: LCP Packets

Code	Packet Type	Description
0x01	Configure-request	Contains the list of proposed options and their values
0x02	Configure-ack	Accepts all options proposed
0x03	Configure-nak	Announces that some options are not acceptable
0x04	Configure-reject	Announces that some options are not recognized
0x05	Terminate-request	Request to shut down the line
0x06	Terminate-ack	Accept the shutdown request
0x07	Code-reject	Announces an unknown code
0x08	Protocol-reject	Announces an unknown protocol
0x09	Echo-request	A type of hello message to check if the other end is alive
0x0A	Echo-reply	The response to the echo-request message
0x0B	Discard-request	A request to discard the packet

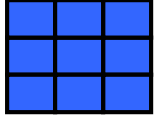


Table 11.2: Common options

Option	*Default*
Maximum receive unit (payload field size)	1500
Authentication protocol	None
Protocol field compression	Off
Address and control field compression	Off

Figure 11.24: PAP packets encapsulated in a PPP frame

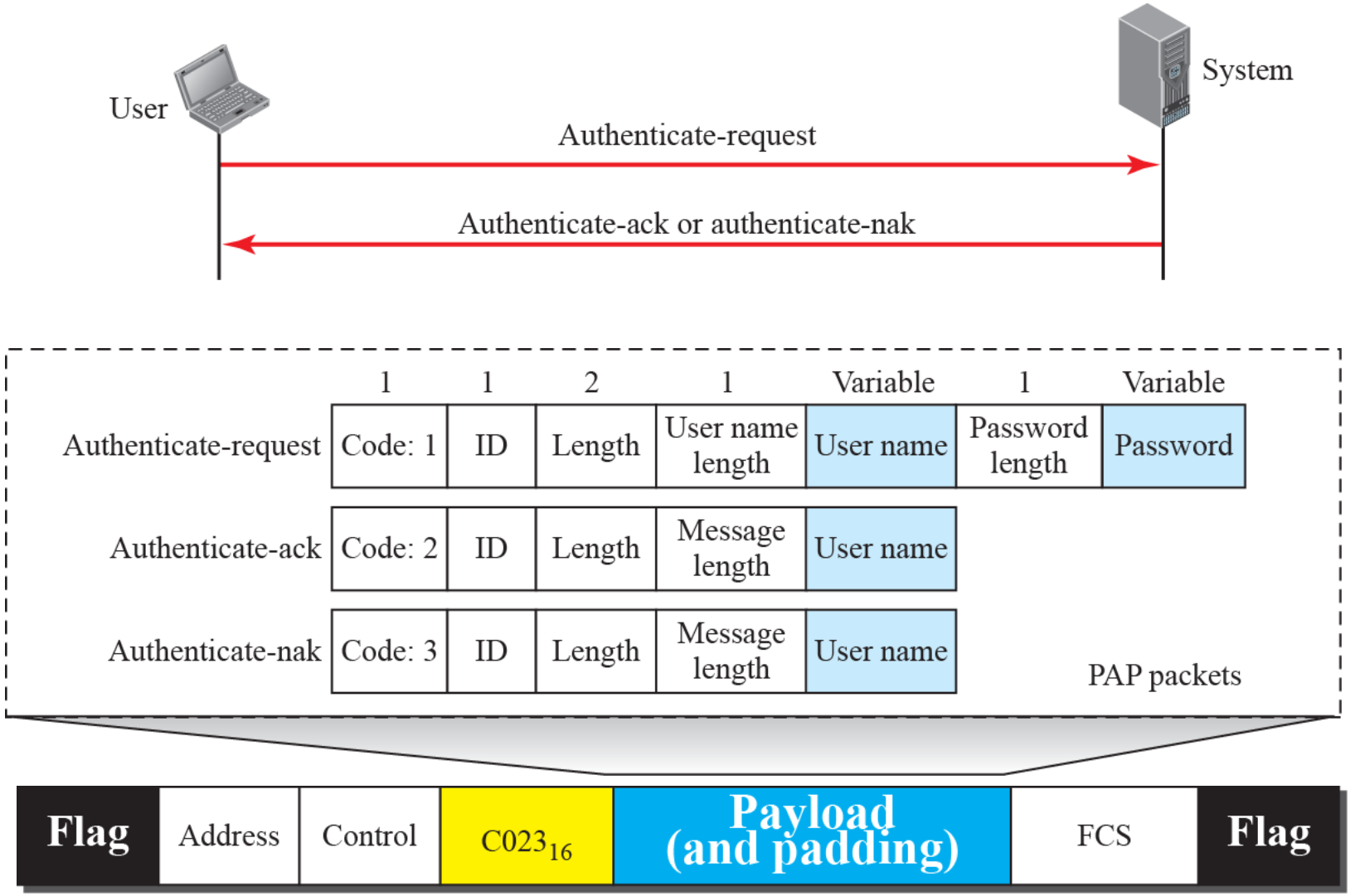


Figure 11.25: CHAP packets encapsulated in a PPP frame

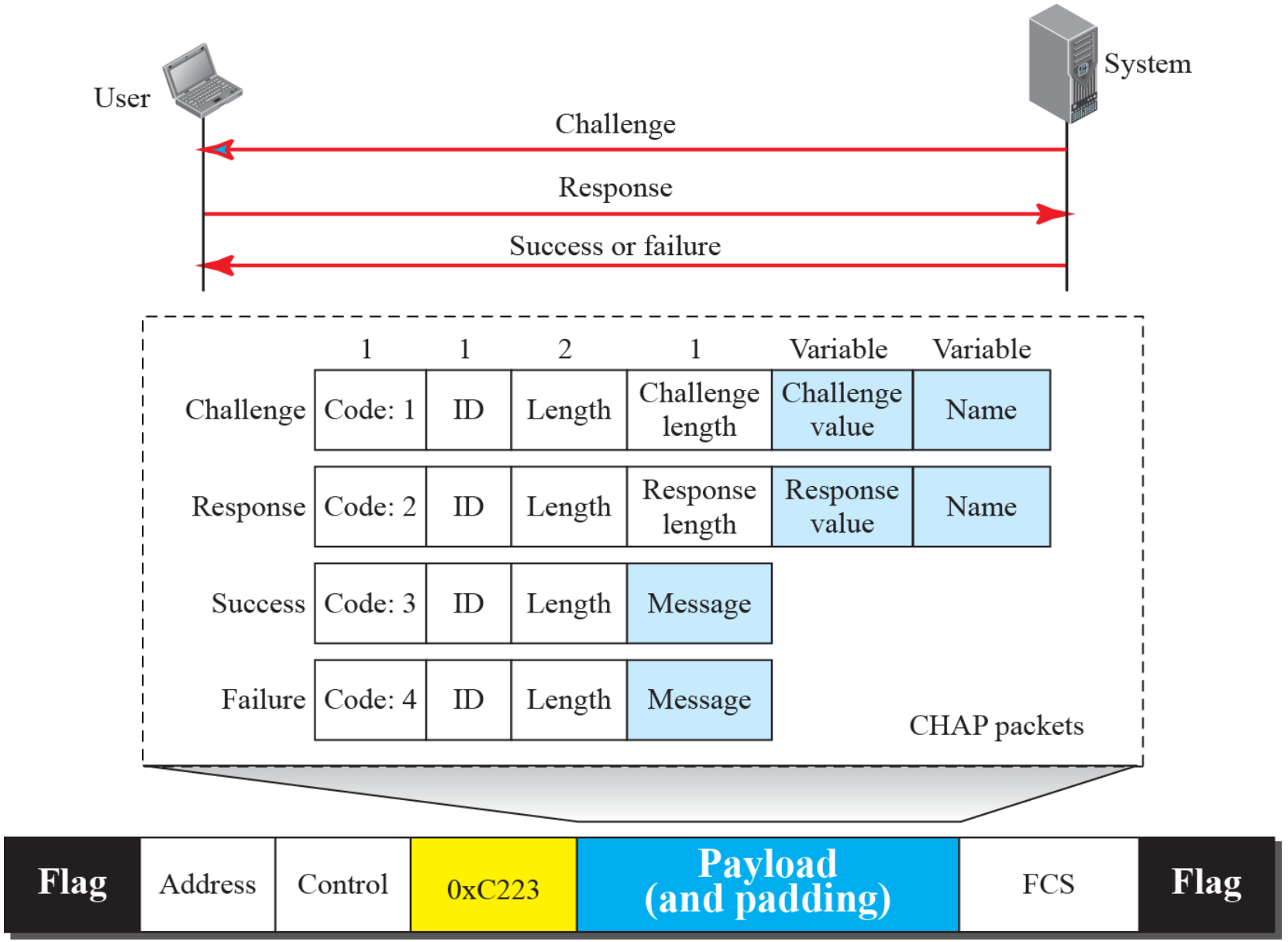
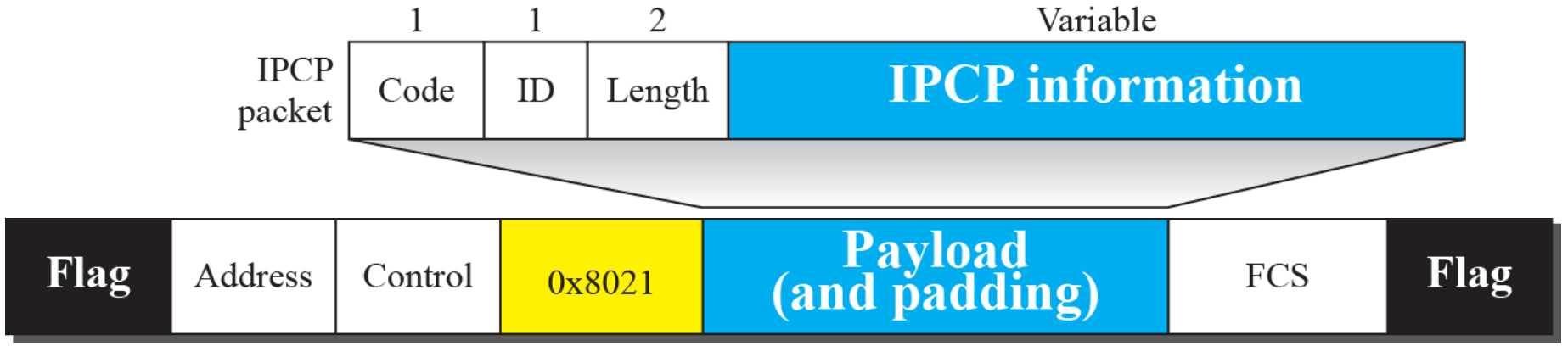


Figure 11.26: IPCP packet encapsulated in PPP frame



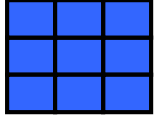


Table 11.3: Code values for IPCP Packets

Code	*IPCP Packet*
0x01	Configure-request
0x02	Configure-ack
0x03	Configure-nak
0x04	Configure-reject
0x05	Terminate-request
0x06	Terminate-ack
0x07	Code-reject

Figure 11.27: IP datagram encapsulated in a PPP frame

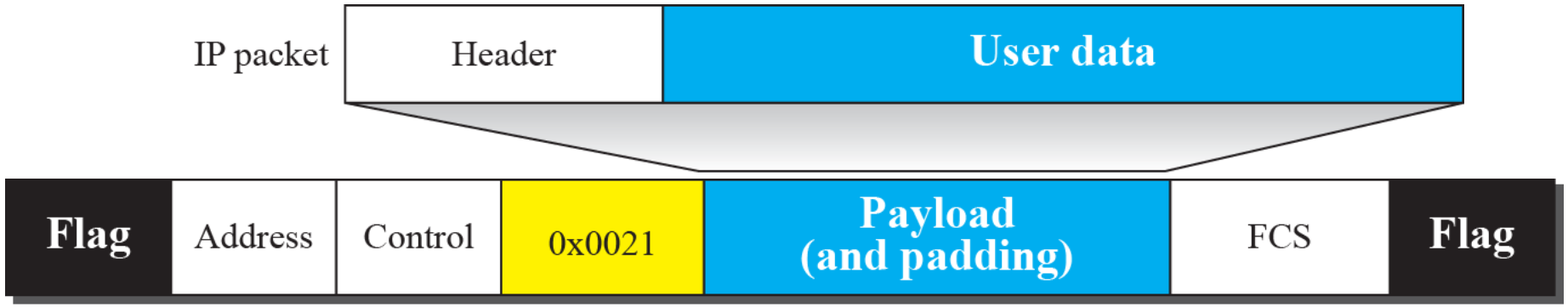
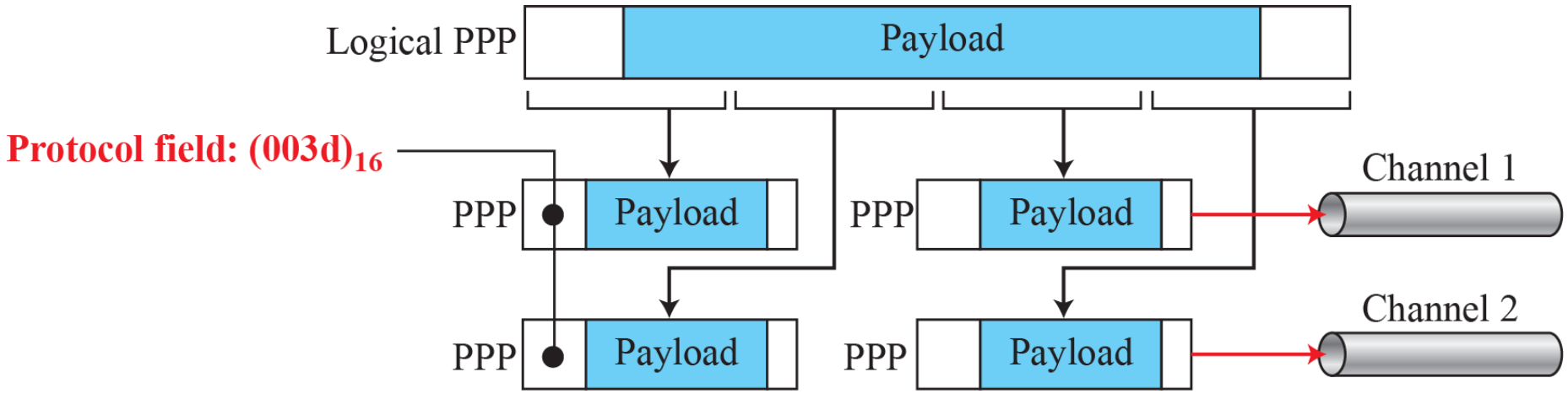


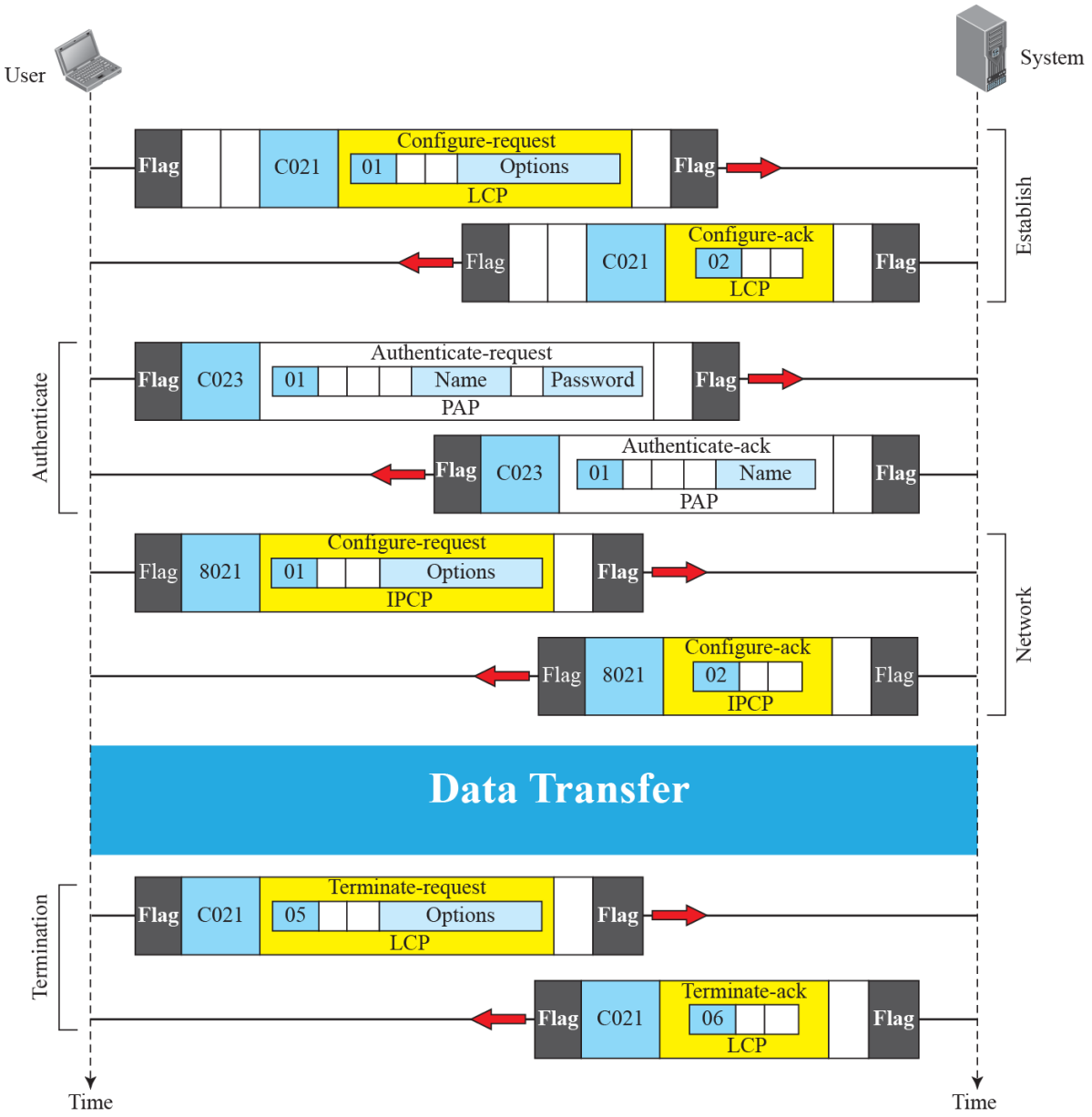
Figure 11.28: Multilink PPP



Example 11.7

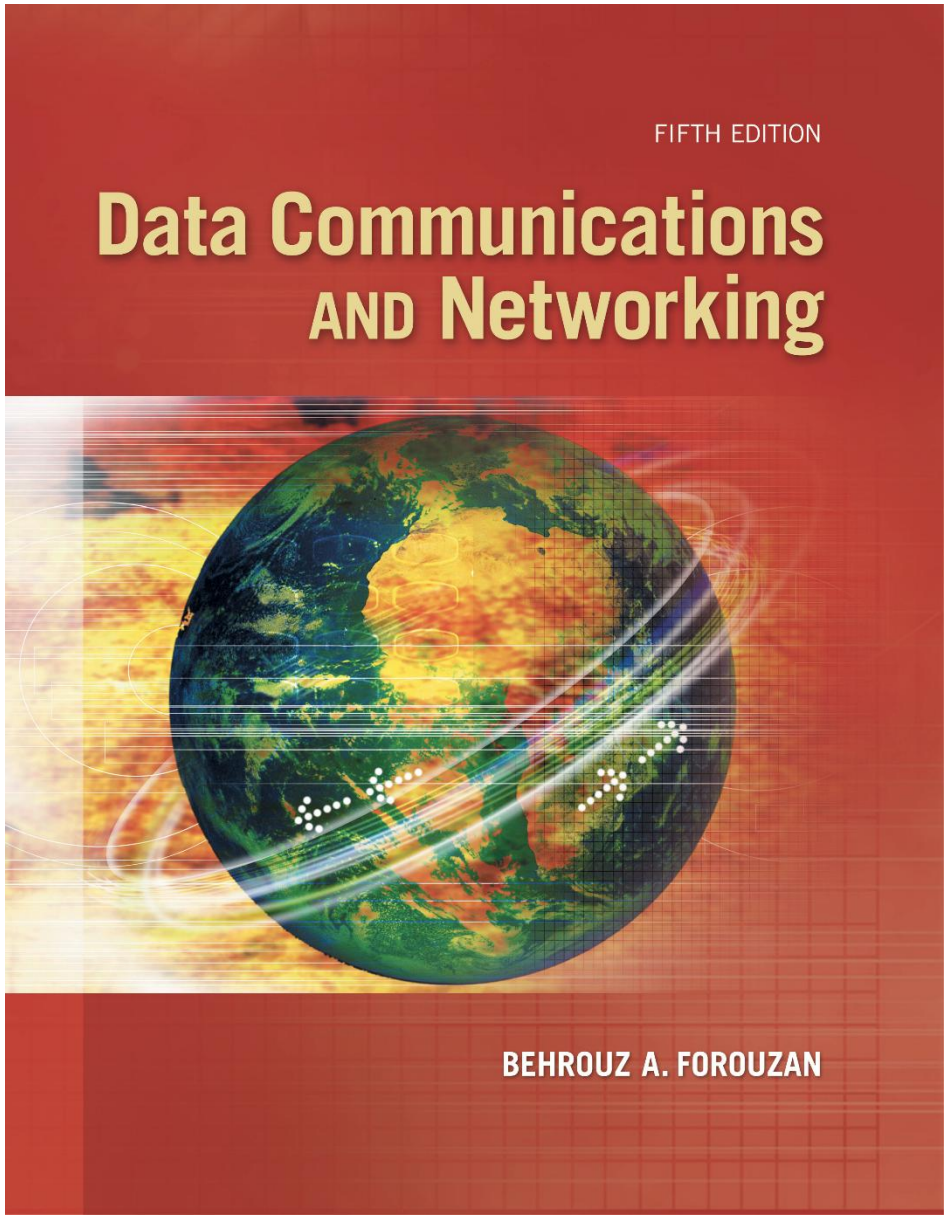
Let us go through the phases followed by a network layer packet as it is transmitted through a PPP connection. Figure 11.29 shows the steps. For simplicity, we assume unidirectional movement of data from the user site to the system site (such as sending an e-mail through an ISP).

Figure 11.29: An example



Chapter 12

Media Access Control (MAC)



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Chapter 5: Outline

12.1 RANDOM ACCESS

12.2 CONTROLLED ACCESS

12.3 CHANNELIZATION

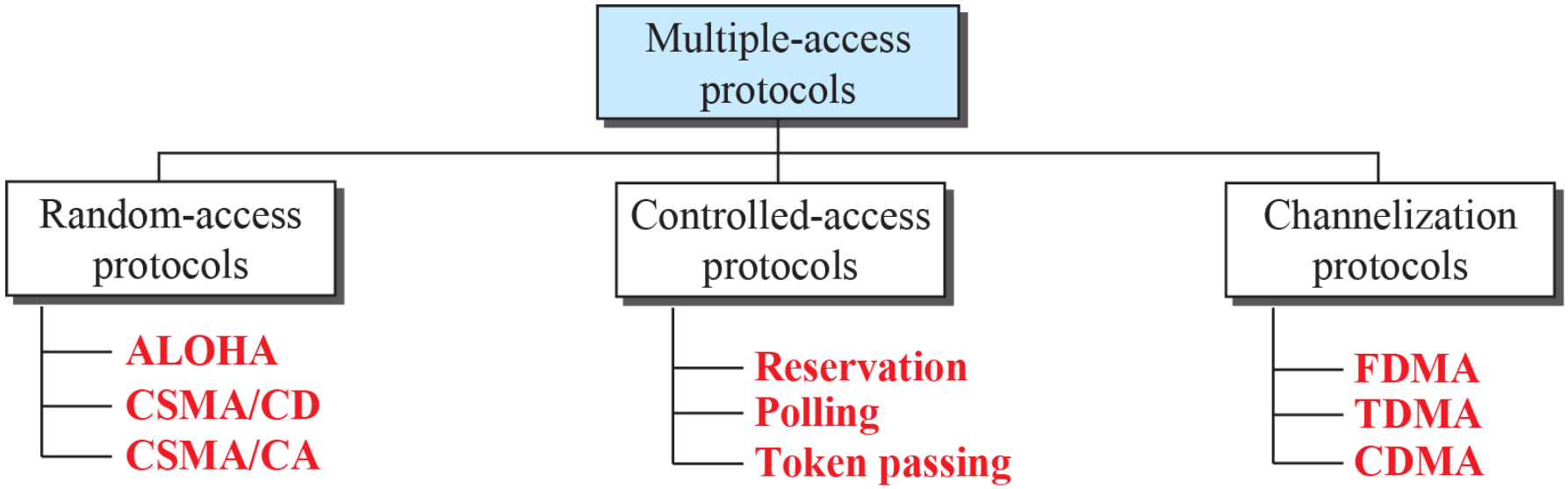
Chapter 12: Objective

- *The first section discusses random-access protocols. Four protocols, ALOHA, CSMA, CSMA/CD, and CSMA/CA, are described in this section. These protocols are mostly used in LANs and WANs, which we discuss in future chapters.*

- *The second section discusses controlled-access protocols. Three protocols, reservation, polling, and token-passing, are described in this section. Some of these protocol are used in LANs, but others have some historical value.*

- *The third section discusses channelization protocols. Three protocols, FDMA, TDMA, and CDMA are described in this section. These protocols are used in cellular telephony, which we discuss in Chapter 16.*

Figure 12.1: Taxonomy of multiple-access protocols



12-1 RANDOM ACCESS

In random-access or contention no station is superior to another station and none is assigned control over another. At each instance, a station that has data to send uses a procedure defined by the protocol to make a decision on whether or not to send. This decision depends on the state of the medium (idle or busy).

12.12.1 ALOHA

ALOHA, the earliest random access method, was developed at the University of Hawaii in early 1970. It was designed for a radio (wireless) LAN, but it can be used on any shared medium. It is obvious that there are potential collisions in this arrangement. The medium is shared between the stations. When a station sends data, another station may attempt to do so at the same time. The data from the two stations collide and become garbled.

Figure 12.2: Frames in a pure ALOHA network

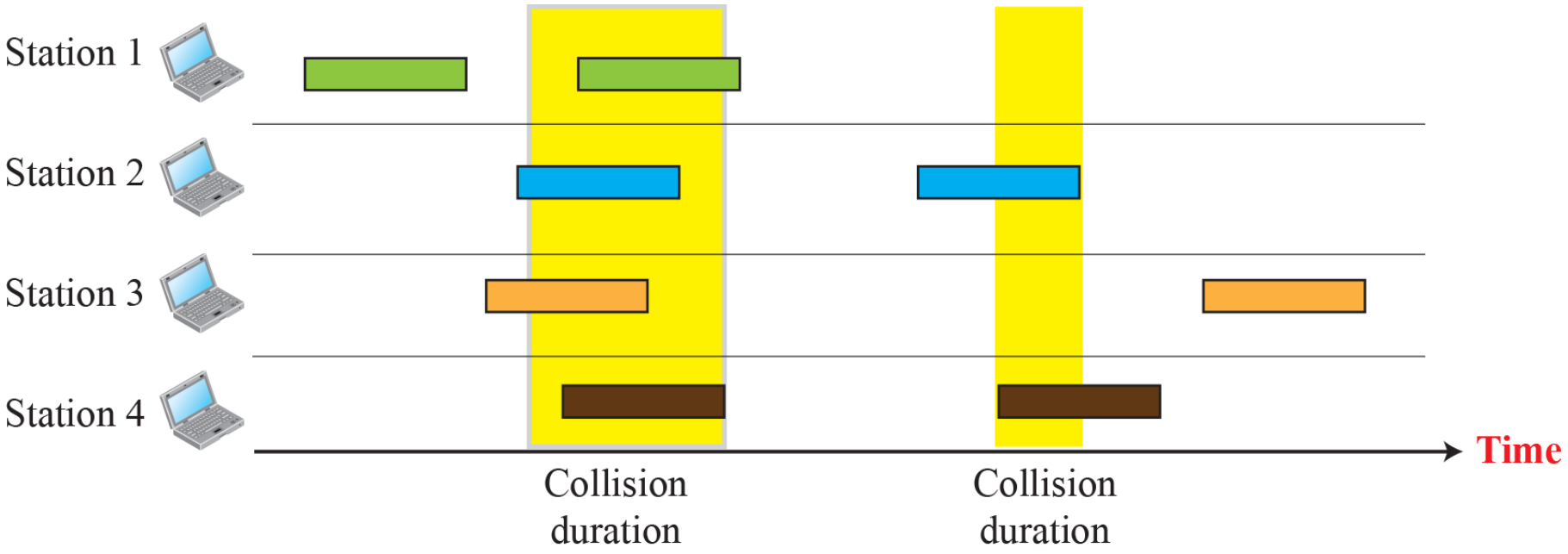
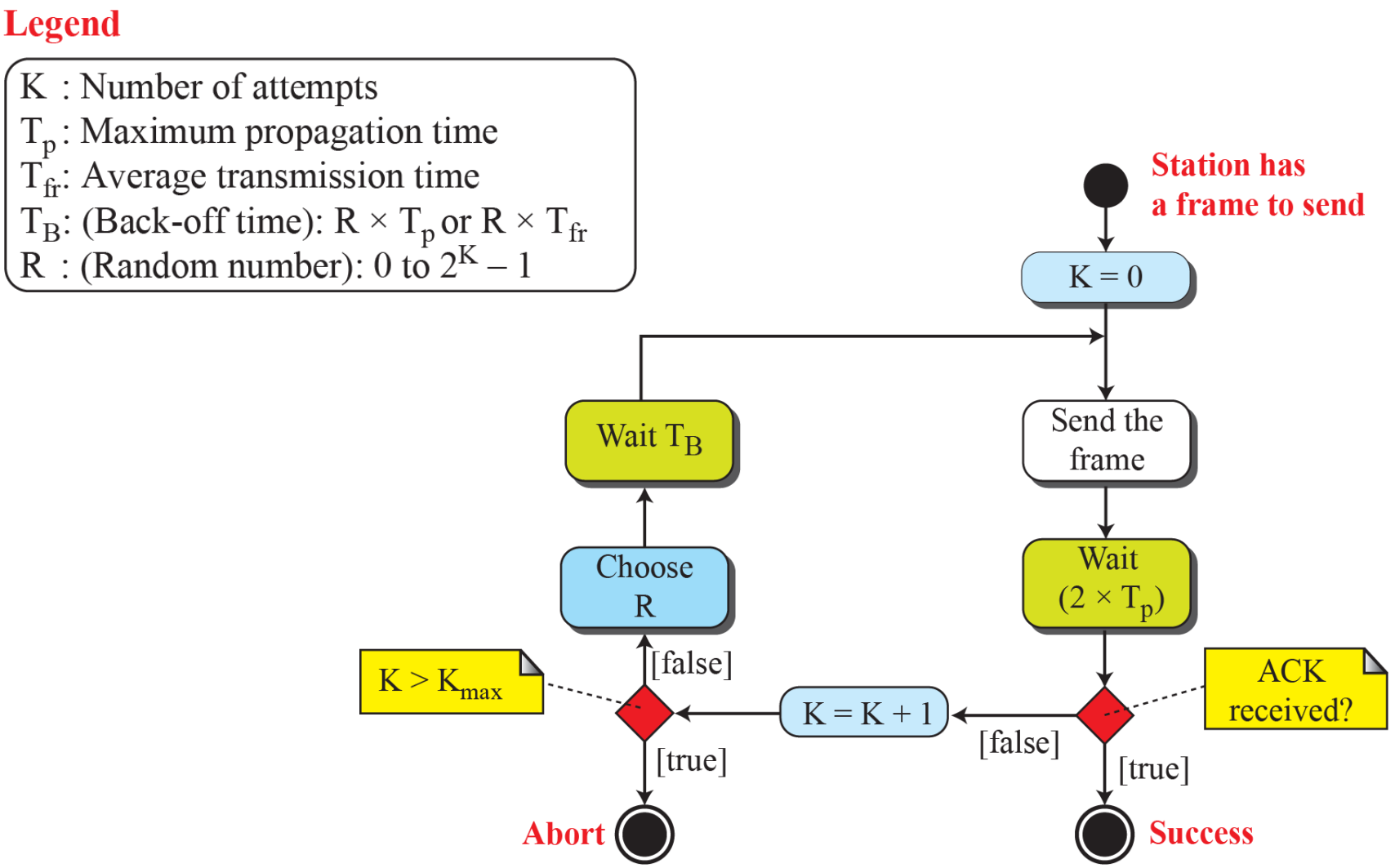


Figure 12.3: Procedure for pure ALOHA protocol

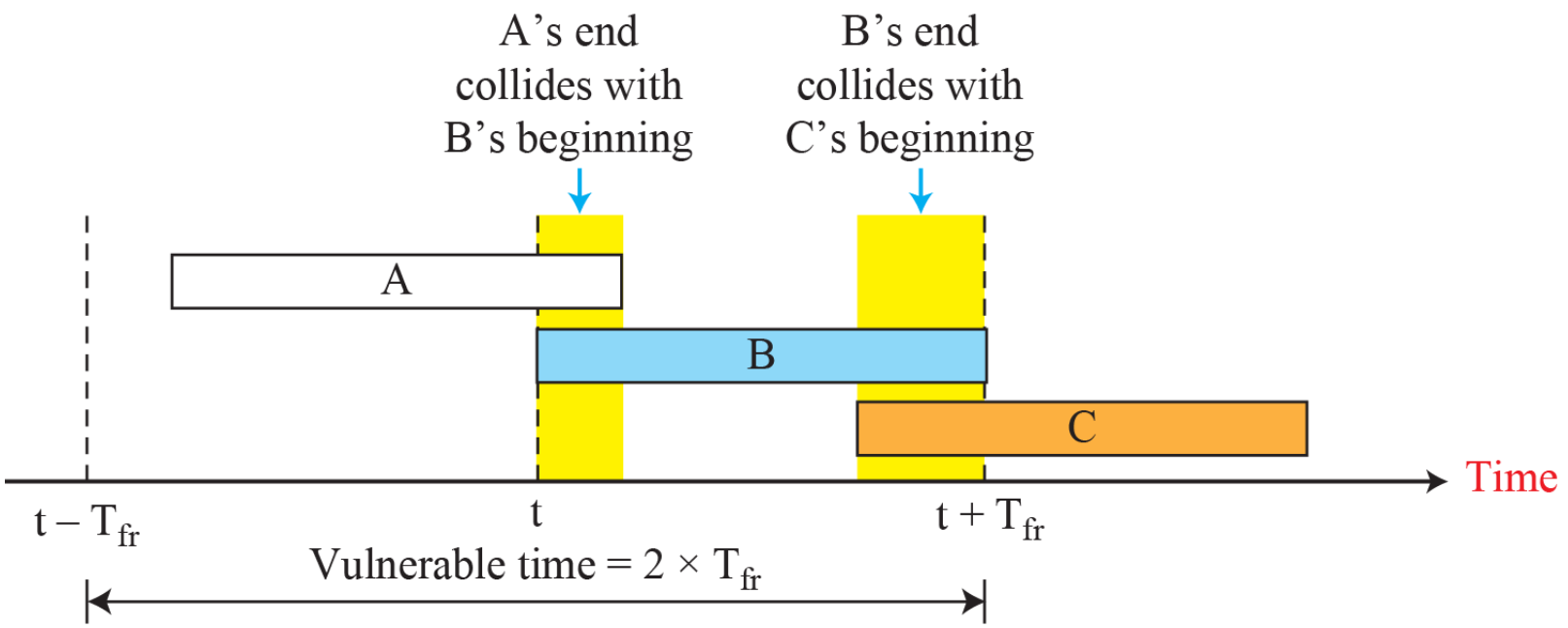


Example 12. 1

The stations on a wireless ALOHA network are a maximum of 600 km apart. If we assume that signals propagate at 3×10^8 m/s, we find $T_p = (600 \times 10^3) / (3 \times 10^8) = 2$ ms. For

$K = 2$, the range of R is {0, 1, 2, 3}. This means that T_B can be 0, 2, 4, or 6 ms, based on the outcome of the random variable R.

Figure 12.4: Vulnerable time for pure ALOHA protocol



Example 12.2

A pure ALOHA network transmits 200-bit frames on a shared channel of 200 kbps. What is the requirement to make this frame collision-free?

Solution

Average frame transmission time T_{fr} is 200 bits/200 kbps or 1 ms. The vulnerable time is 2×1 ms = 2 ms. This means no station should send later than 1 ms before this station starts transmission and no station should start sending during the period (1 ms) that this station is sending.

Example 12. 3

A pure ALOHA network transmits 200-bit frames on a shared channel of 200 kbps. What is the throughput if the system (all stations together) produces

a. 1000 frames per second?

b. 500 frames per second?

c. 250 frames per second?

Solution

The frame transmission time is 200/200 kbps or 1 ms.

a. If the system creates 1000 frames per second, or 1 frame per millisecond, then G = 12. In this case $S = G \times e^{-2G} =$ 0.135 (13.5 percent). This means that the throughput is $1000 \times 0.135 = 135$ frames. Only 135 frames out of 1000

 will probably survive.

교과서 오류 수정

- G = average no. of transmission attempts per frame time
- Each **frame** has a **vulnerable period** of **2 frame times**, during which **any** other transmission causes a **collision**
- Therefore, a frame is transmitted **successfully** only if **no other transmission occurs** during the entire 2-frame vulnerable period
- So, the **probability of a successful transmission** is:

$$\Pr[k] = \frac{G^k \cdot e^{-G}}{k!}$$

$$P_0 = \Pr[\text{no other transmission in 2 frame times}] = e^{-2G}$$

교과서 오류 수정

- Hence $S = G \cdot e^{-2G}$
  - is the throughput per frame time
- Note that **S is still defined per frame time**, **not per 2 frame times**. The *vulnerable period* is 2 frame times, but the **rate** and **throughput** are still per one frame time
- Then, Probability of no collisions = $P_0 = e^{-2G}$
- Throughput per frame time = $\boxed{S = G \cdot e^{-2G}}$

교과서 오류 수정

- G=0.5 means **on average**, 0.5 transmission attempts **per frame time**
- So over **1000 frame times**, the **total number of attempted transmissions** is:
  - total attempts = G * 1000 = 500
- The throughput per frame time is

$$S = G \cdot e^{-2G} = 0.5 \cdot e^{-1} \approx 0.1839$$

- So the **total number of successful transmissions** over 1000 frame times is

$$1000 \cdot S = 1000 \cdot 0.1839 \approx 184$$

교과서 오류 수정

- Note that the **fraction** of successful transmissions is:

$$P_0 = \frac{S}{G} = e^{-2G} = e^{-1} \approx 0.3679$$

- So,

$$\text{Successful transmissions} = \text{Attempts} \cdot P_0 = 500 \cdot 0.3679 = \boxed{184}$$

$$\boxed{\text{184 frames survive out of 500 attempted over 1000 frame times}}$$

b. If the system creates 500 frames per second, or 1/2 frames per millisecond, then G = 1/2. In this case $S = G \times e^{-2G}$ = 0.184 (18.4 percent). This means that the throughput is 500 × 0.184 = 92 and that only 92 frames out of 500 will probably survive. Note that this is the maximum throughput case, percentage-wise.

c. If the system creates 250 frames per second, or 1/4 frames per millisecond, then G = 1/4. In this case $S = G \times e^{-2G}$ = 0.152 (15.2 percent). This means that the throughput is 250 × 0.152 = 38. Only 38 frames out of 250 will probably survive

Figure 12.5: Frames in a slotted ALOHA network

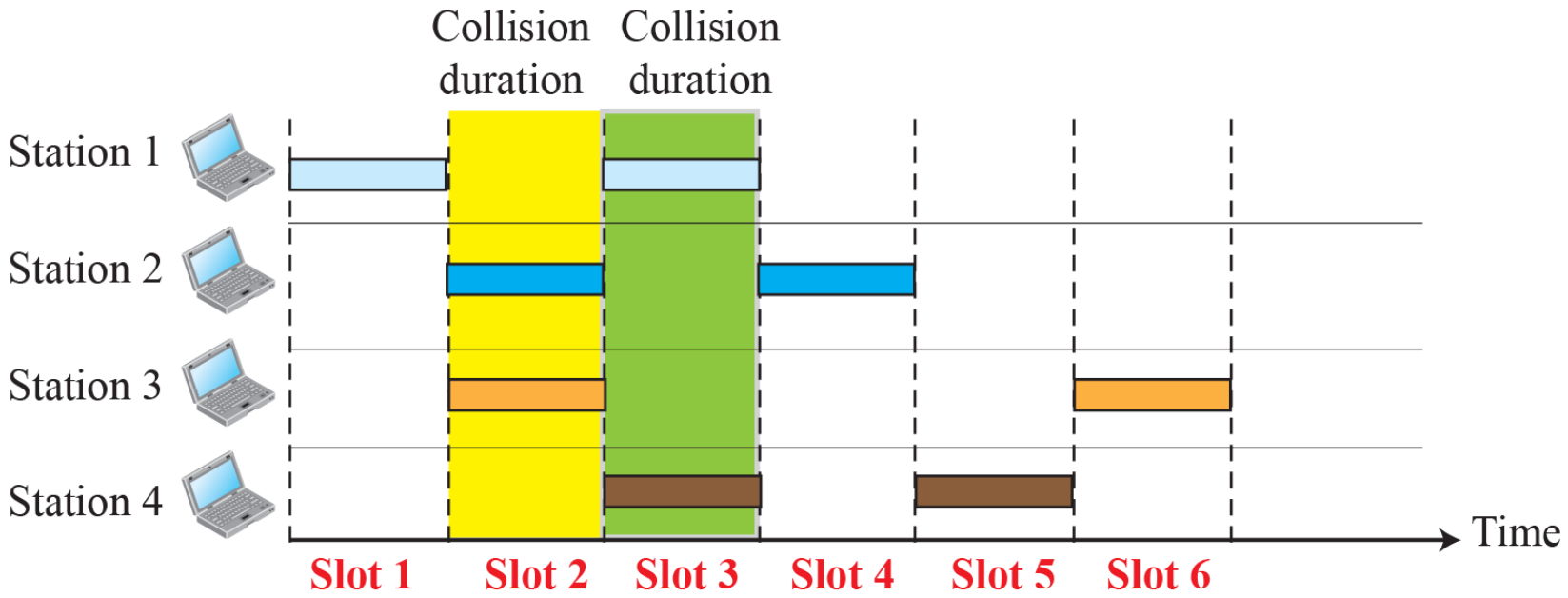
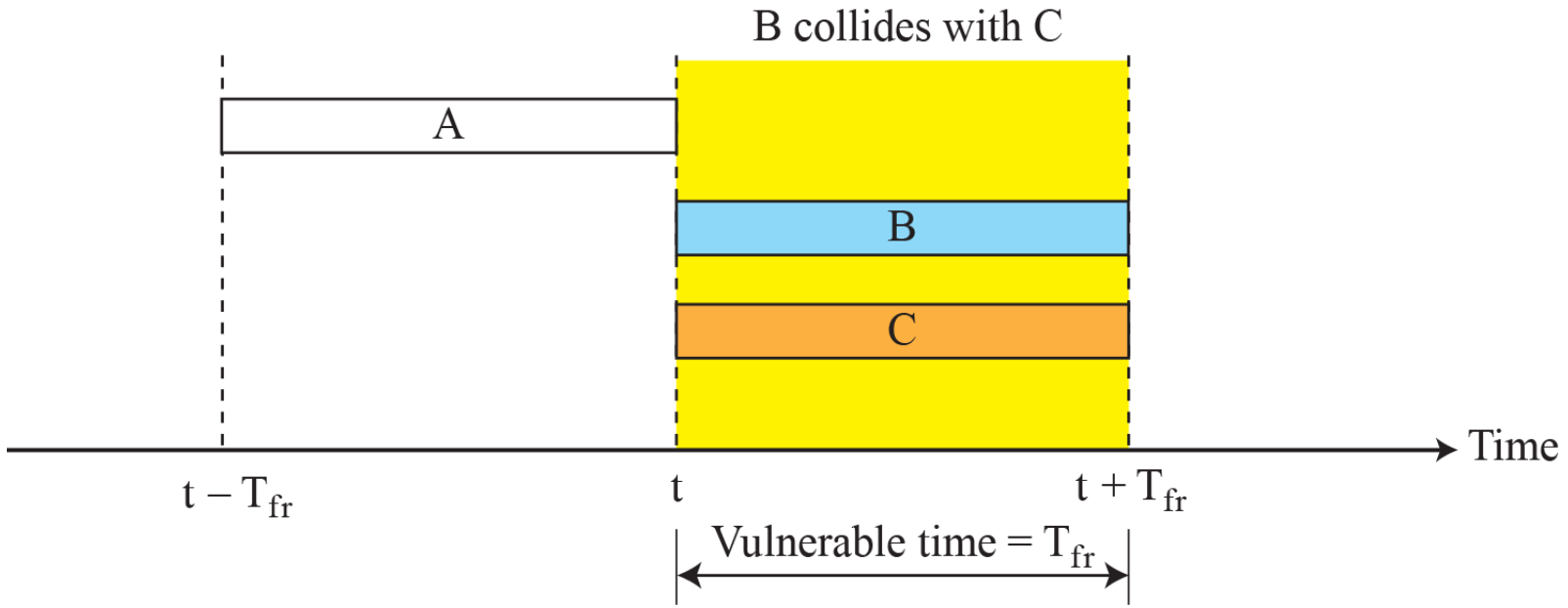


Figure 12.6: Vulnerable time for slotted ALOHA protocol



Example 12. 4

A slotted ALOHA network transmits 200-bit frames using a shared channel with a 200-kbps bandwidth. Find the throughput if the system (all stations together) produces

a. 1000 frames per second.
b. 500 frames per second.
c. 250 frames per second.

Solution

This situation is similar to the previous exercise except that the network is using slotted ALOHA instead of pure ALOHA. The frame transmission time is 200/200 kbps or 1 ms.

Example 12. 4 (continued)

a) In this case G is 12. So $S = G \times e^{-G} = 0.368$ (36.8 percent). This means that the throughput is $1000 \times 0.0368 = 368$ frames. Only 368 out of 1000 frames will probably survive. Note that this is the maximum throughput case, percentage-wise.

b) Here G is 1/2. In this case $S = G \times e^{-G} = 0.303$ (30.3 percent). This means that the throughput is $500 \times 0.0303 = 1512$. Only 151 frames out of 500 will probably survive.

c) Now G is 1/4. In this case $S = G \times e^{-G} = 0.195$ (19.5 percent). This means that the throughput is $250 \times 0.195 = 49$. Only 49 frames out of 250 will probably survive.

12.12.2 CSMA

To minimize the chance of collision and, therefore, increase the performance, the CSMA method was developed. The chance of collision can be reduced if a station senses the medium before trying to use it. Carrier sense multiple access (CSMA) requires that each station first listen to the medium (or check the state of the medium) before sending. In other words, CSMA is based on the principle "sense before transmit" or "listen before talk."

Figure 12.7: Space/time model of a collision in CSMA

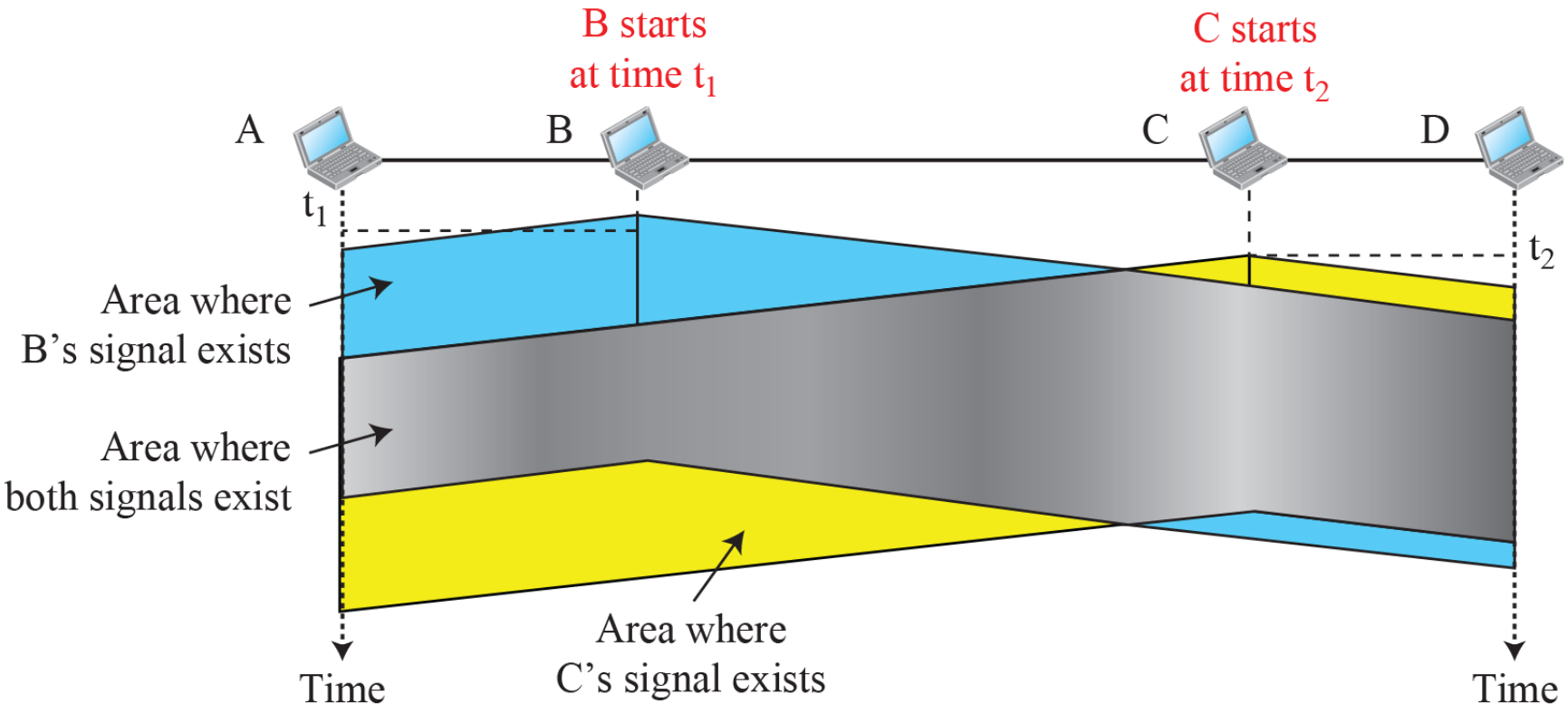


Figure 12.8: Vulnerable time in CSMA

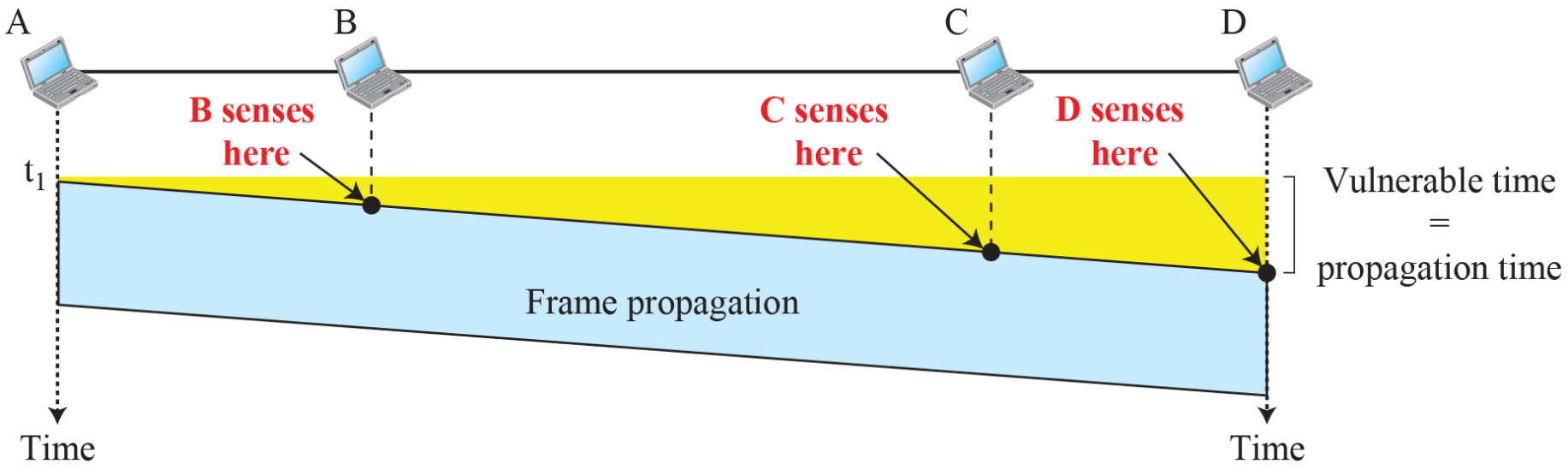
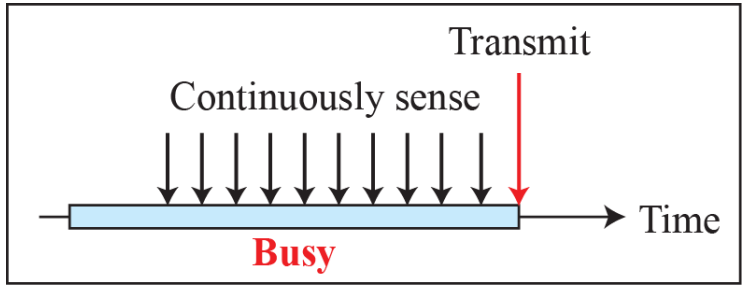
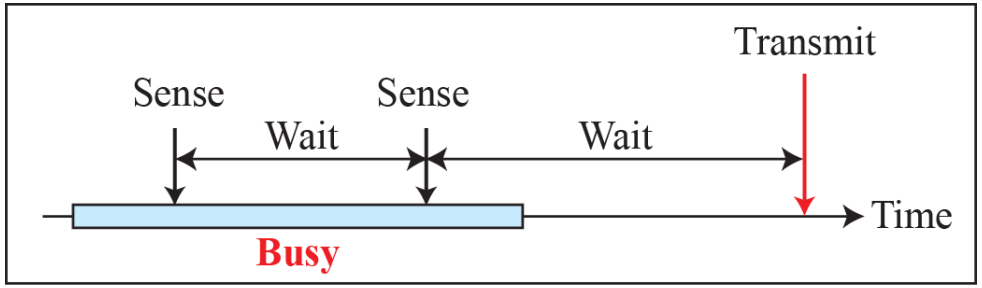


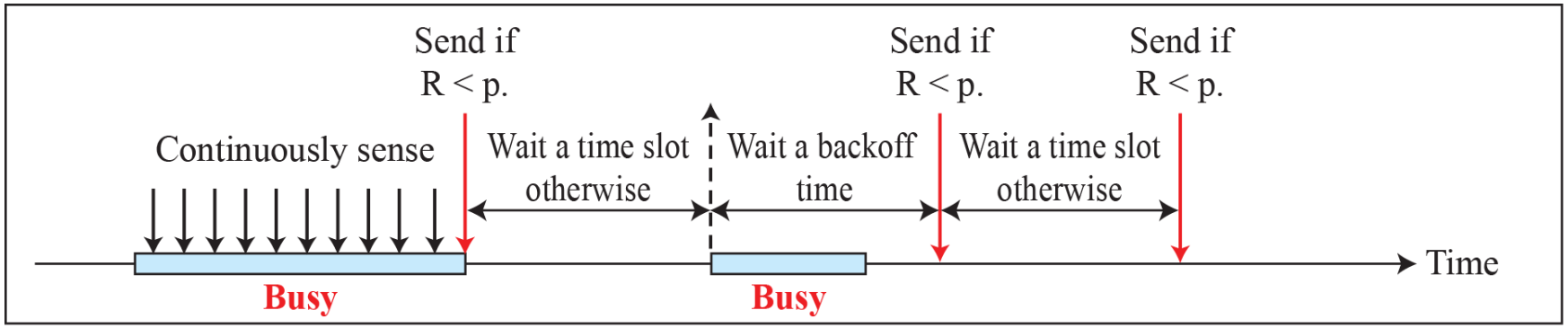
Figure 12.9: Behavior of three persistence methods



a. 1-persistent

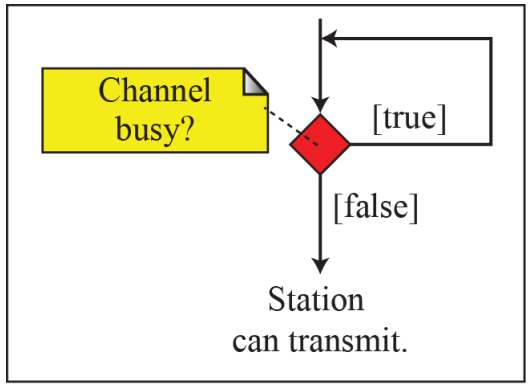


b. Nonpersistent

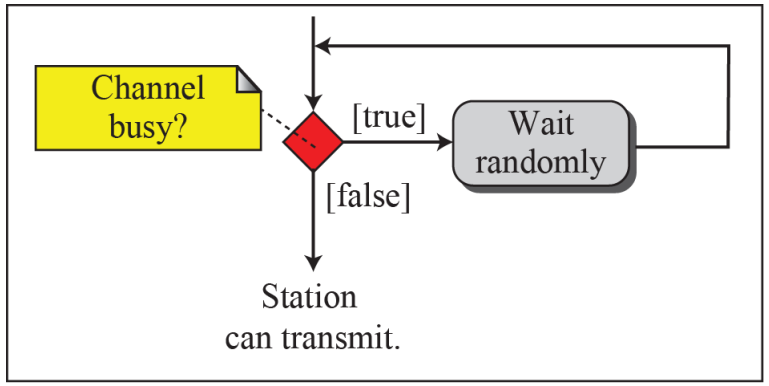


c. *p*-persistent

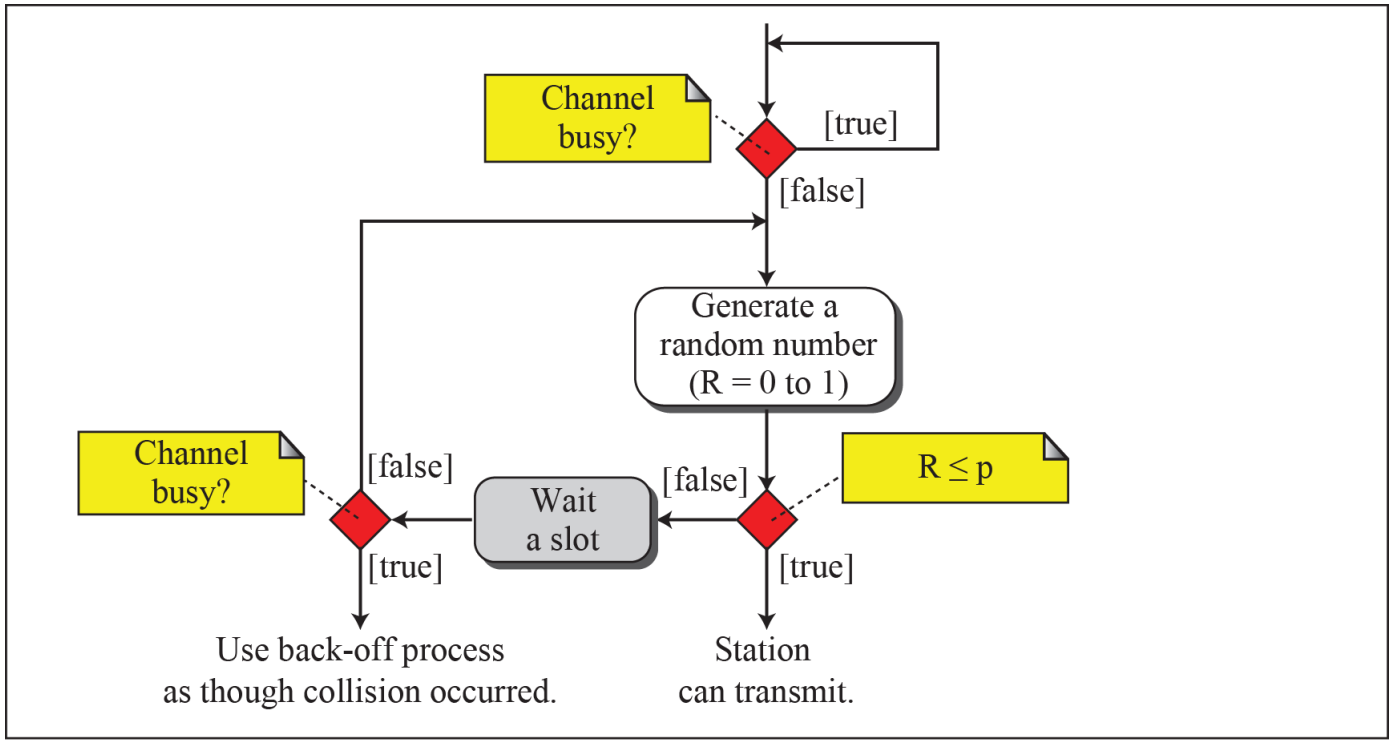
Figure 12.10: Flow diagram for three persistence methods



a. 1-persistent



b. Nonpersistent



c. *p*-persistent

12.12.3 CSMA/CD

The CSMA method does not specify the procedure following a collision. Carrier sense multiple access with collision detection (CSMA/CD) augments the algorithm to handle the collision.

In this method, a station monitors the medium after it sends a frame to see if the transmission was successful. If so, the station is finished. If, however, there is a collision, the frame is sent again.

Figure 12.11: Collision of the first bits in CSMA/CD

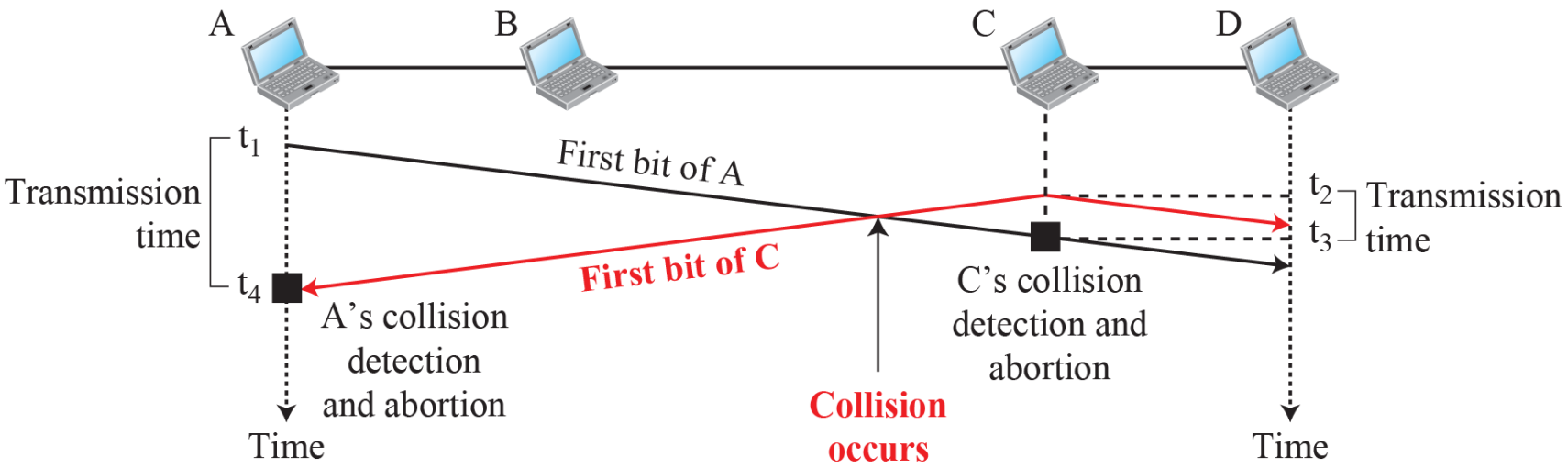
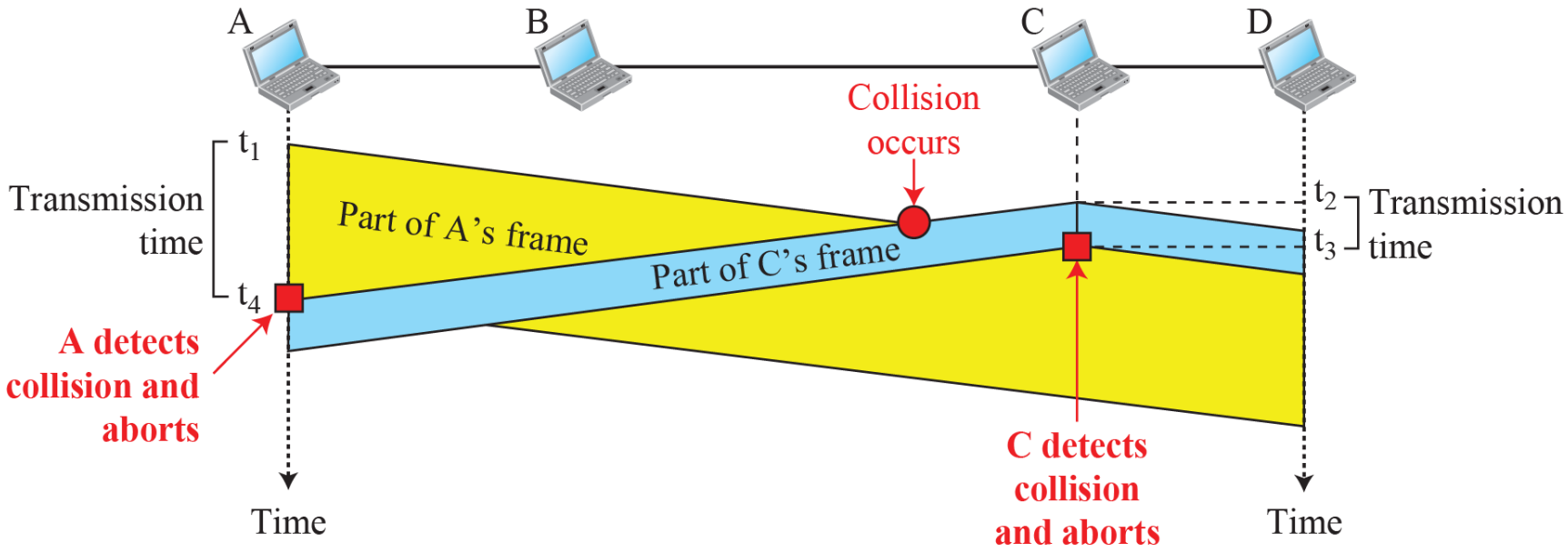


Figure 12.12: Collision and abortion in CSMA/CD



Example 12. 5

A network using CSMA/CD has a bandwidth of 10 Mbps. If the maximum propagation time (including the delays in the devices and ignoring the time needed to send a jamming signal, as we see later) is 25.6 μs, what is the minimum size of the frame?

Solution

The minimum frame transmission time is $T_{fr} = 2 \times T_p = 512.2$ μs. This means, in the worst case, a station needs to transmit for a period of 512.2 μs to detect the collision. The minimum size of the frame is 10 Mbps × 512.2 μs = 512 bits or 64 bytes. This is actually the minimum size of the frame for Standard Ethernet, as we will see later in the chapter.

Figure 12.13: Flow diagram for the CSMA/CD

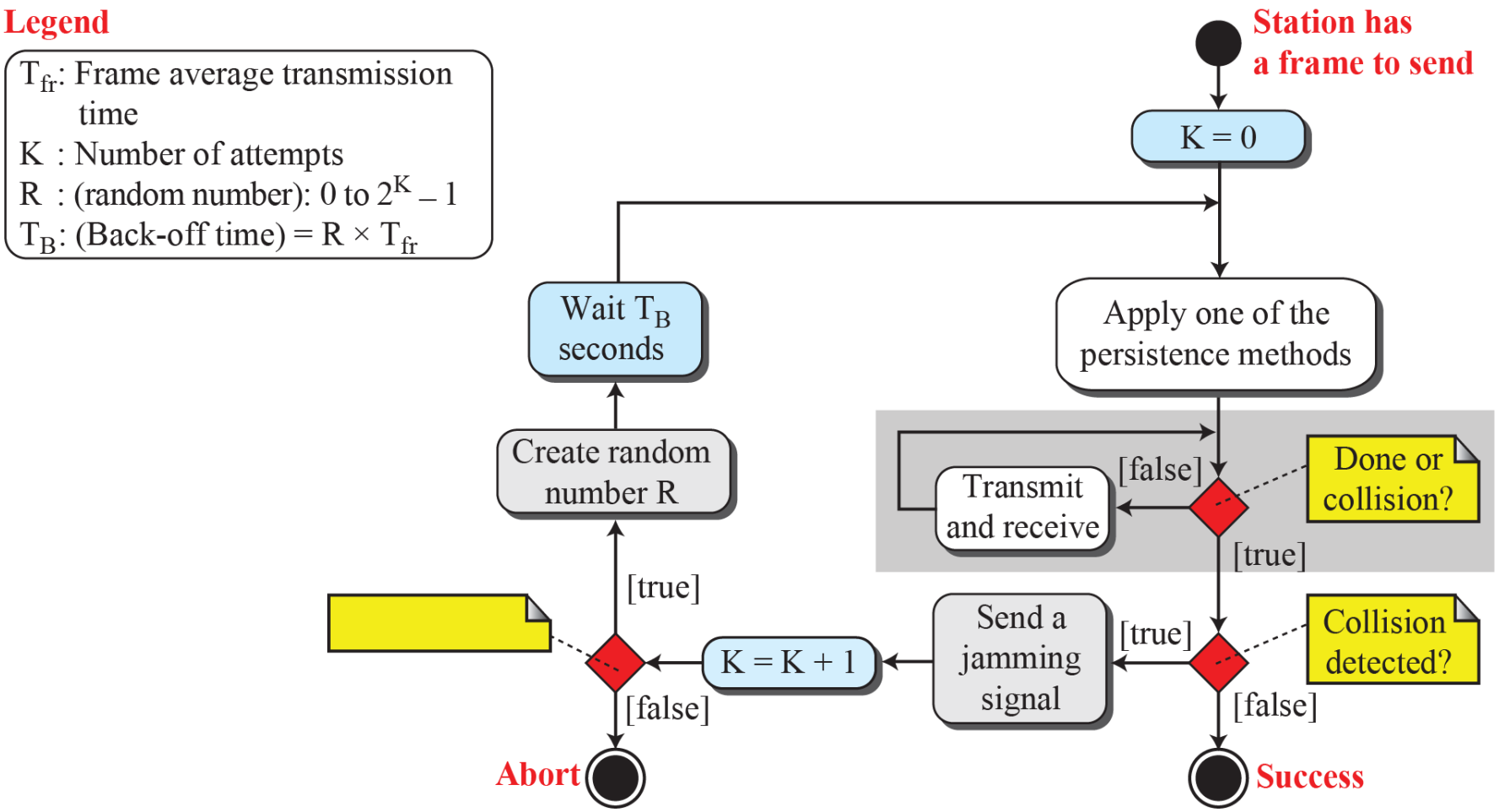
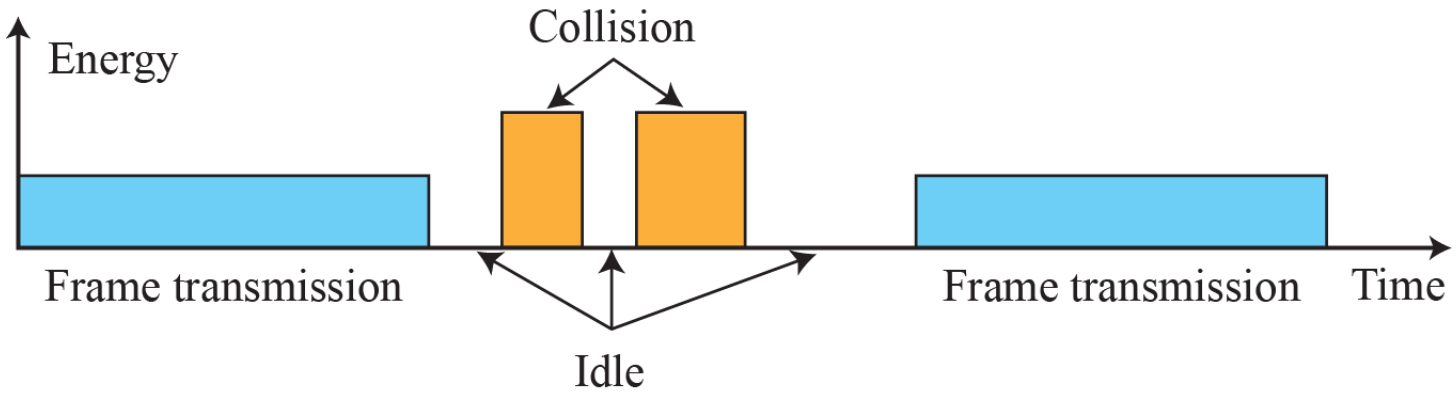


Figure 12.14: Energy level during transmission, idleness, or collision



12.12.4 CSMA/CA

Carrier sense multiple access with collision avoidance (CSMA/CA) was invented for wireless networks. Collisions are avoided through the use of CSMA/CA's three strategies: the interframe space, the contention window, and acknowledgments, as shown in Figure 12.15. We discuss RTS and CTS frames later.

Figure 12.15: Flow diagram for CSMA/CA

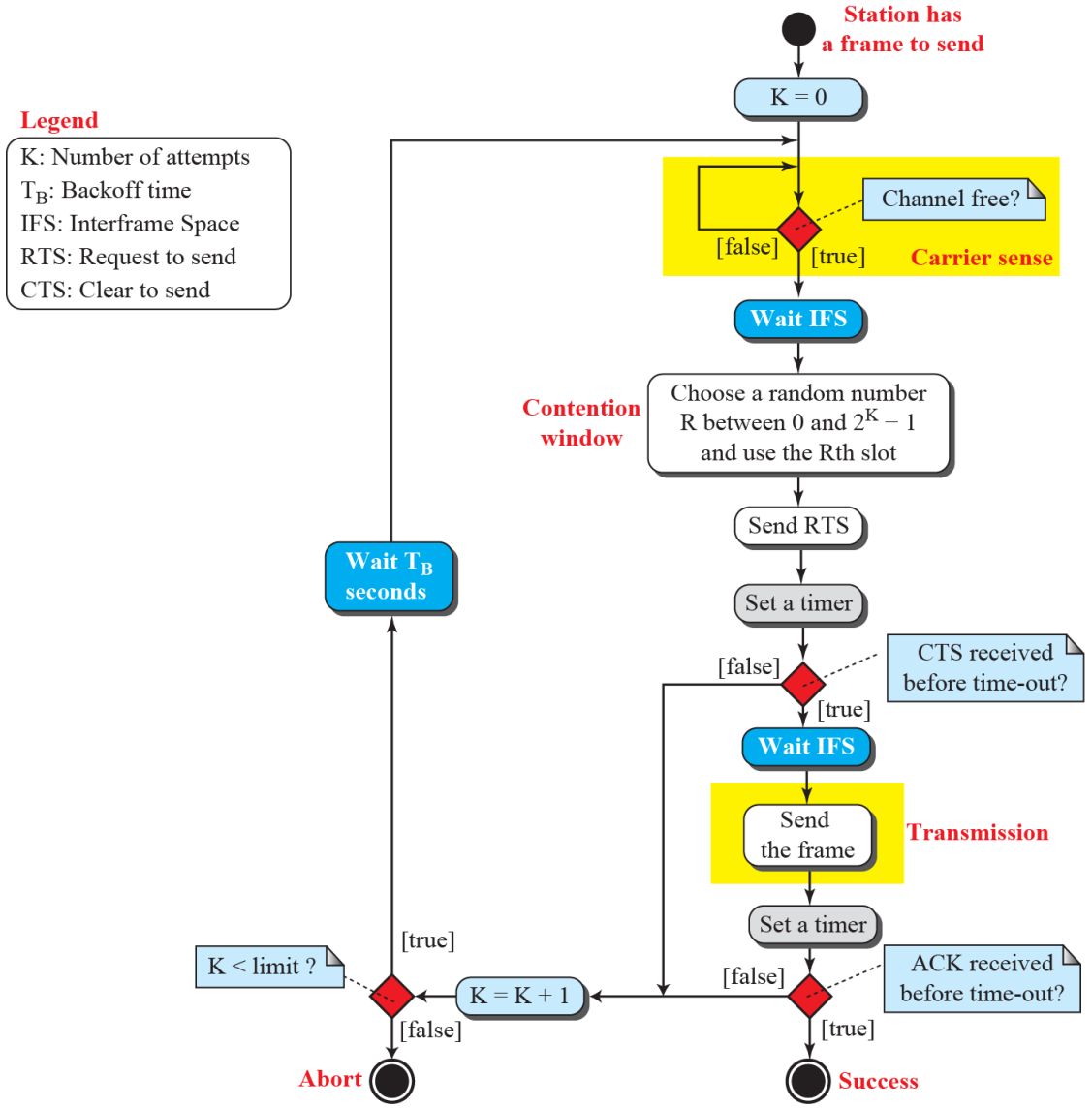


Figure 12.16: Contention window

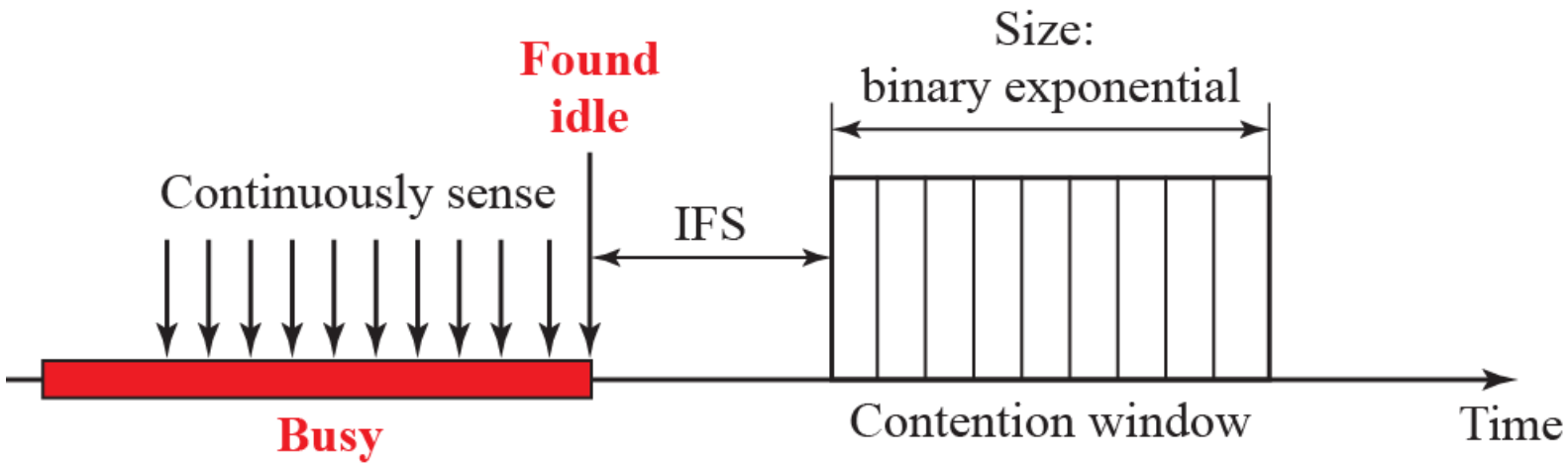
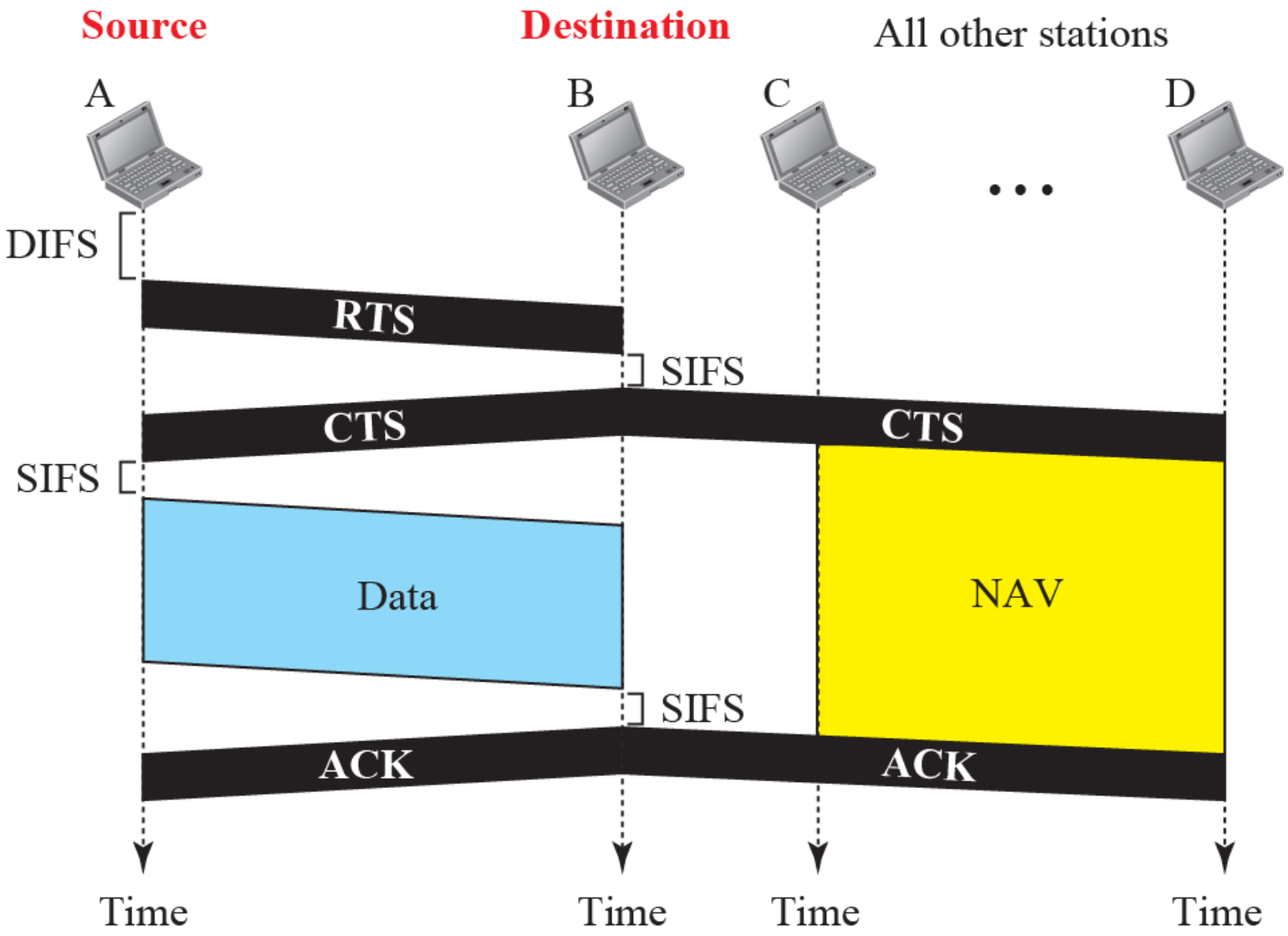


Figure 12.17: CMACA and NAV



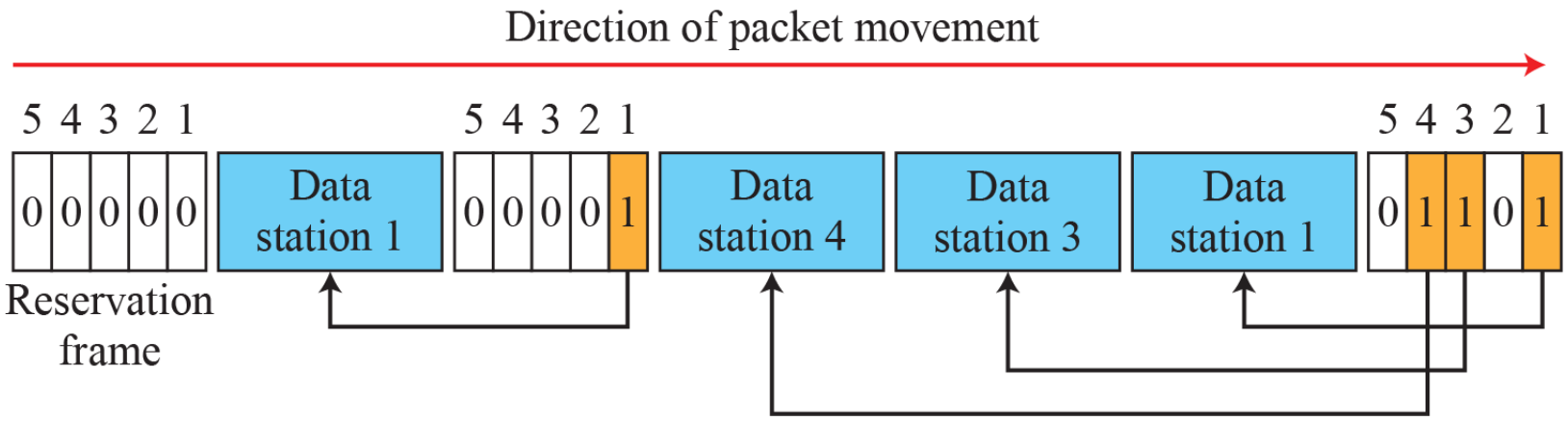
12-2 CONTROLLED ACCESS

In controlled access, the stations consult one another to find which station has the right to send. A station cannot send unless it has been authorized by other stations. We discuss three controlled-access methods.

12.2.1 Reservation

In the reservation method, a station needs to make a reservation before sending data. Time is divided into intervals. In each interval, a reservation frame precedes the data frames sent in that interval.

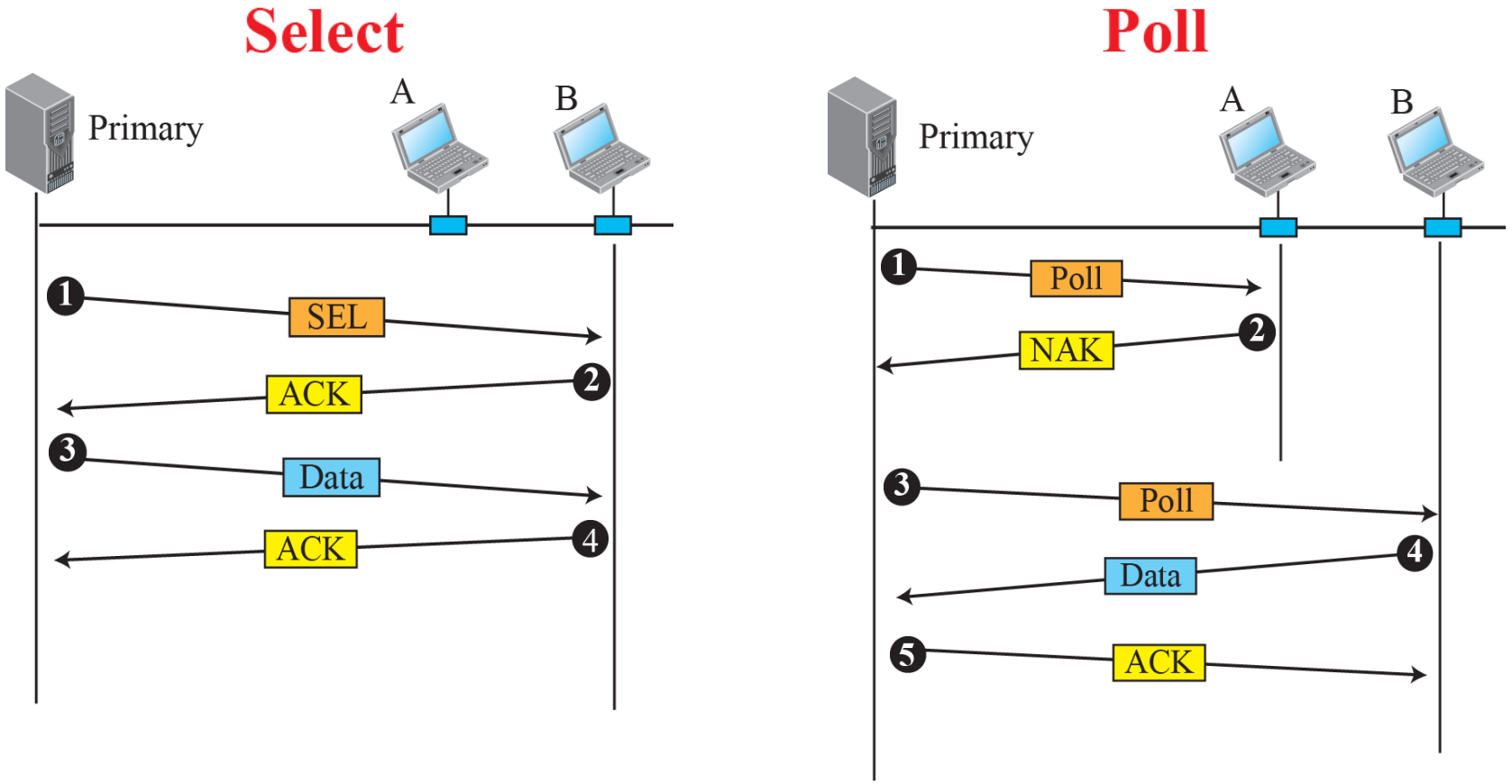
Figure 12.18: Reservation access method



12.2.2 Polling

Polling works with topologies in which one device is designated as a primary station and the other devices are secondary stations. All data exchanges must be made through the primary device even when the ultimate destination is a secondary device. The primary device controls the link; the secondary devices follow its instructions. It is up to the primary device to determine which device is allowed to use the channel at a given time.

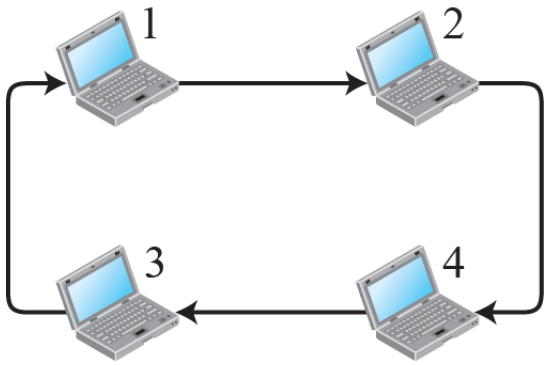
Figure 12.19: Select and poll functions in polling-access method



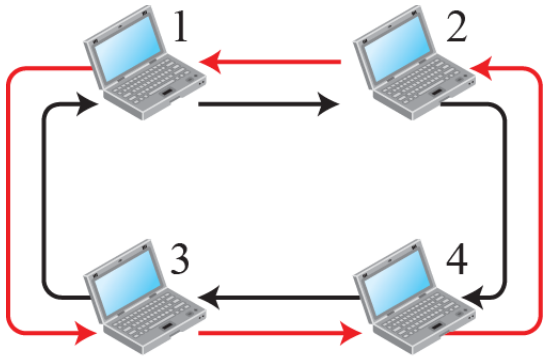
12.2.3 Token Passing

In the token-passing method, the stations in a network are organized in a logical ring. In other words, for each station, there is a predecessor and a successor. The predecessor is the station which is logically before the station in the ring; the successor is the station which is after the station in the ring.

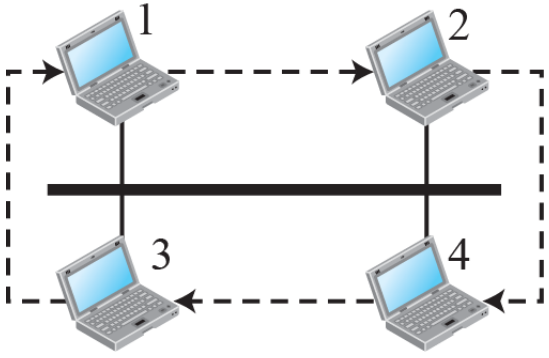
Figure 12.20: Logical ring and physical topology in token-passing access method



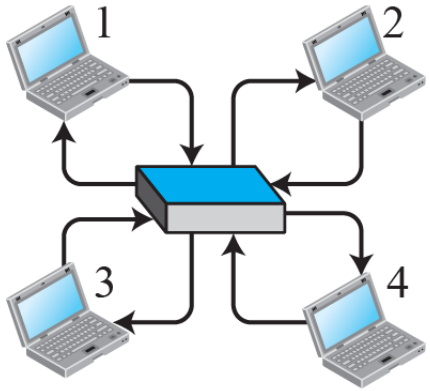
a. Physical ring



b. Dual ring



c. Bus ring



d. Star ring

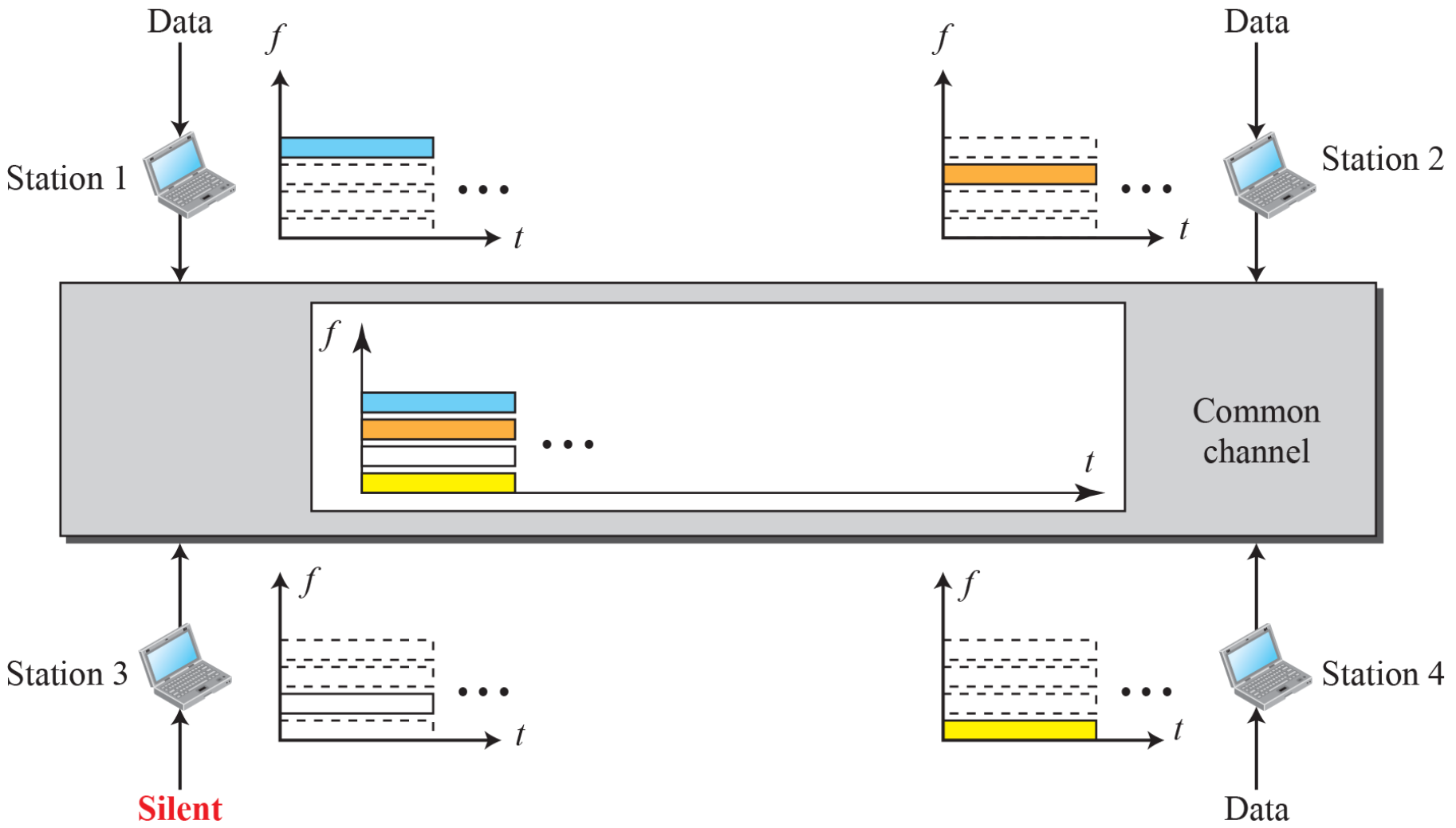
12-3 CHANNELIZATION

Channelization (or channel partition, as it is sometimes called) is a multiple-access method in which the available bandwidth of a link is shared in time, frequency, or through code, among different stations. In this section, we discuss three protocols: FDMA, TDMA, and CDMA.

12.3.1 FDMA

In frequency-division multiple access (FDMA), the available bandwidth is divided into frequency bands. Each station is allocated a band to send its data. In other words, each band is reserved for a specific station, and it belongs to the station all the time. Each station also uses a bandpass filter to confine the transmitter frequencies. To prevent

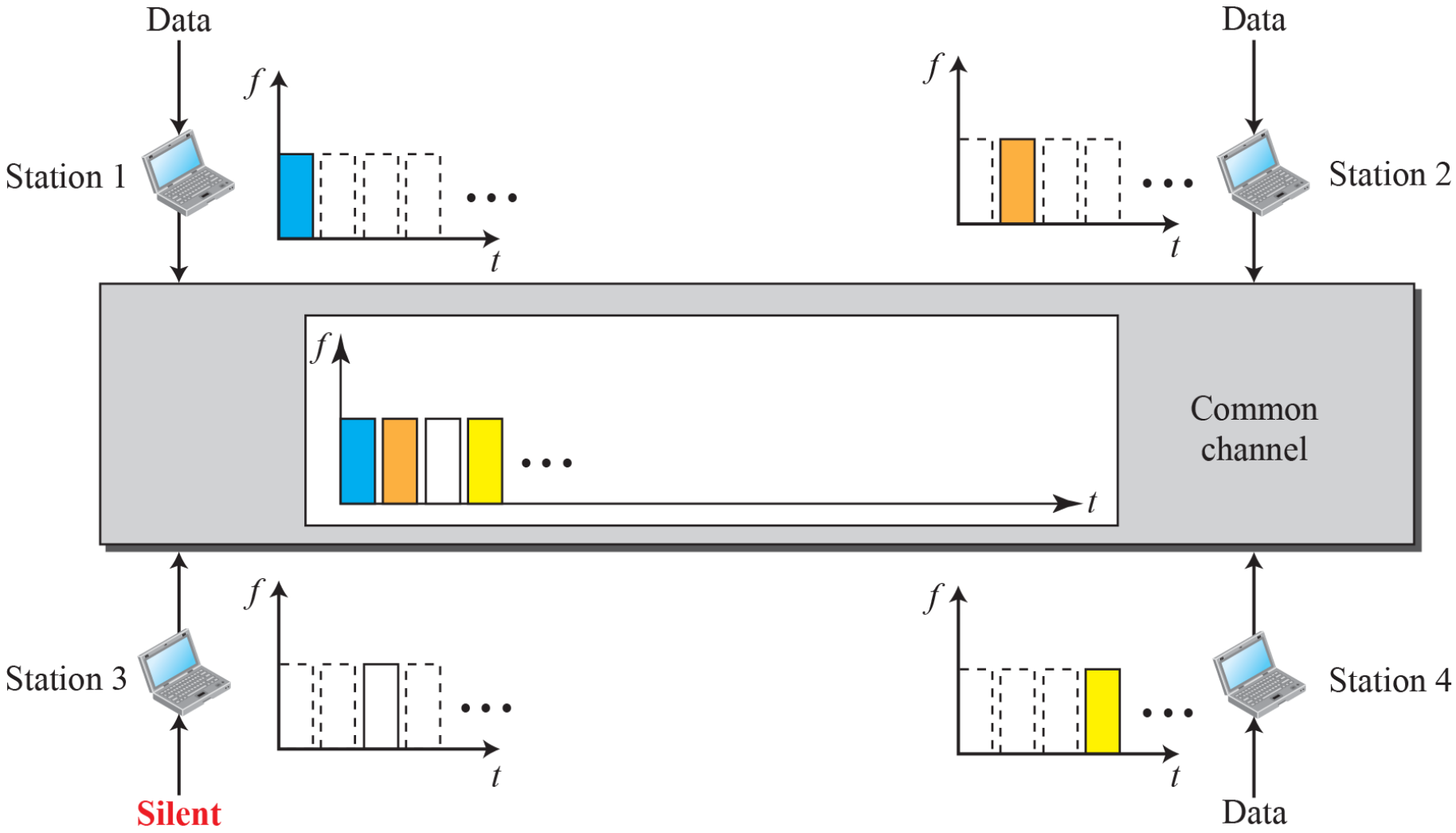
Figure 12.21: Frequency-division multiple access (FDMA)



12.3.2 TDMA

In time-division multiple access (TDMA), the stations share the bandwidth of the channel in time. Each station is allocated a time slot during which it can send data. Each station transmits its data in its assigned time slot. Figure 12.22 shows the idea behind TDMA.

Figure 12.22: Time-division multiple access (TDMA)



12.3.3 CDMA

Code-division multiple access (CDMA) was conceived several decades ago. Recent advances in electronic technology have finally made its implementation possible. CDMA differs from FDMA in that only one channel occupies the entire bandwidth of the link. It differs from TDMA in that all stations can send data simultaneously; there is no timesharing.

Figure 12.23: Simple idea of communication with code

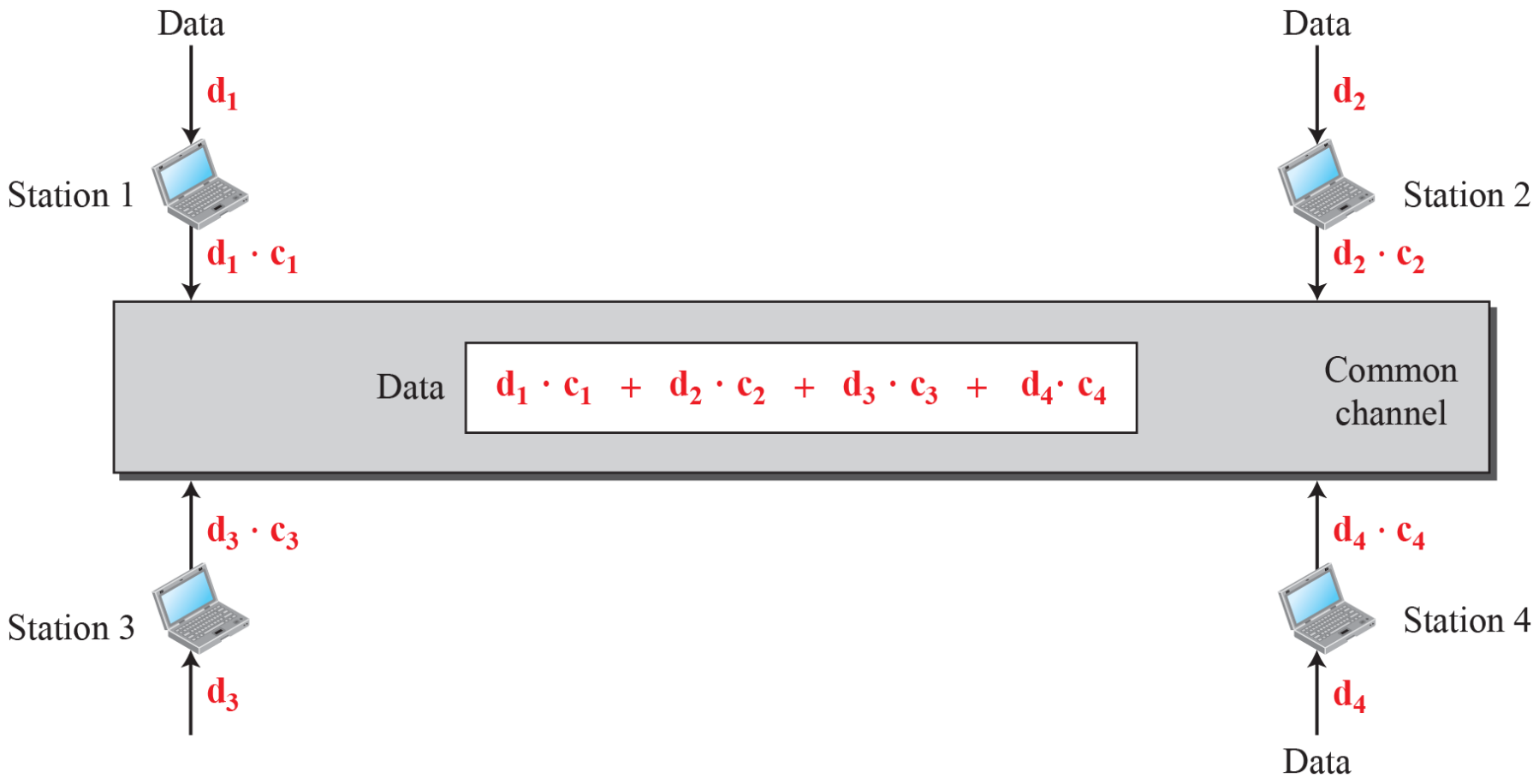


Figure 12.24: Chip sequences

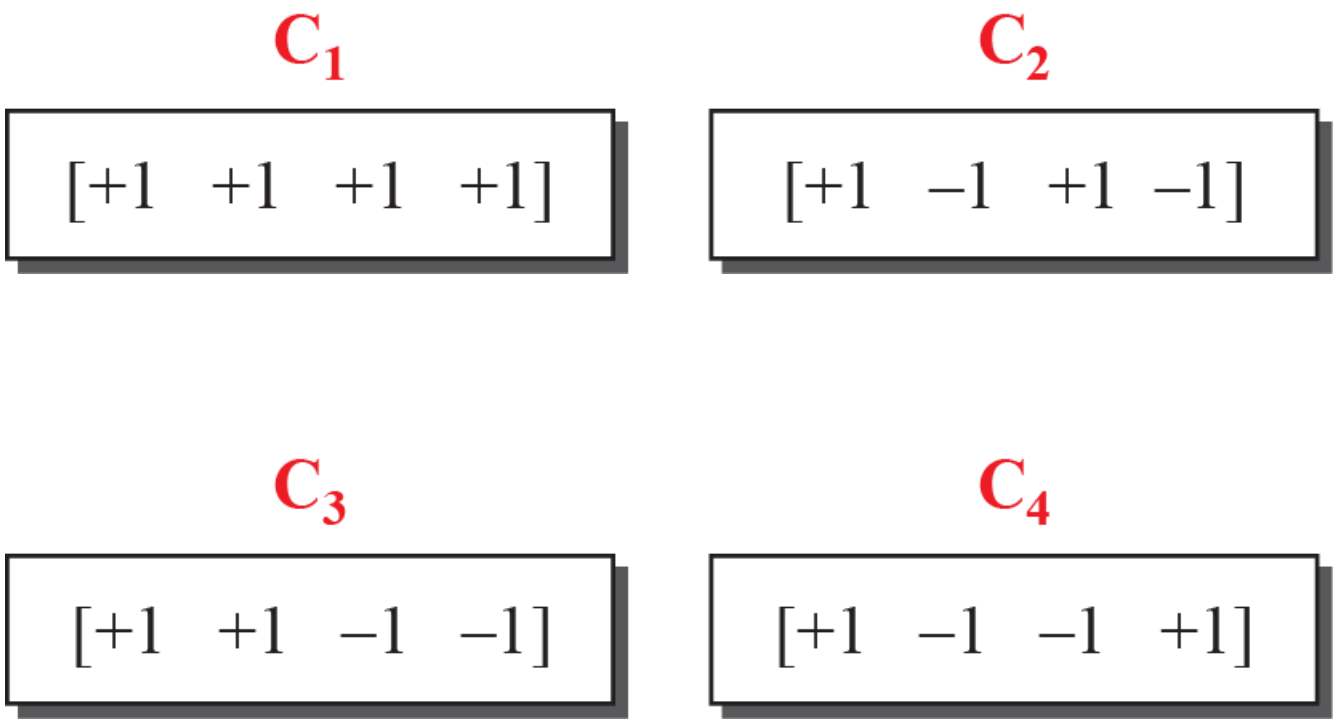


Figure 12.25: Data representation in CDMA

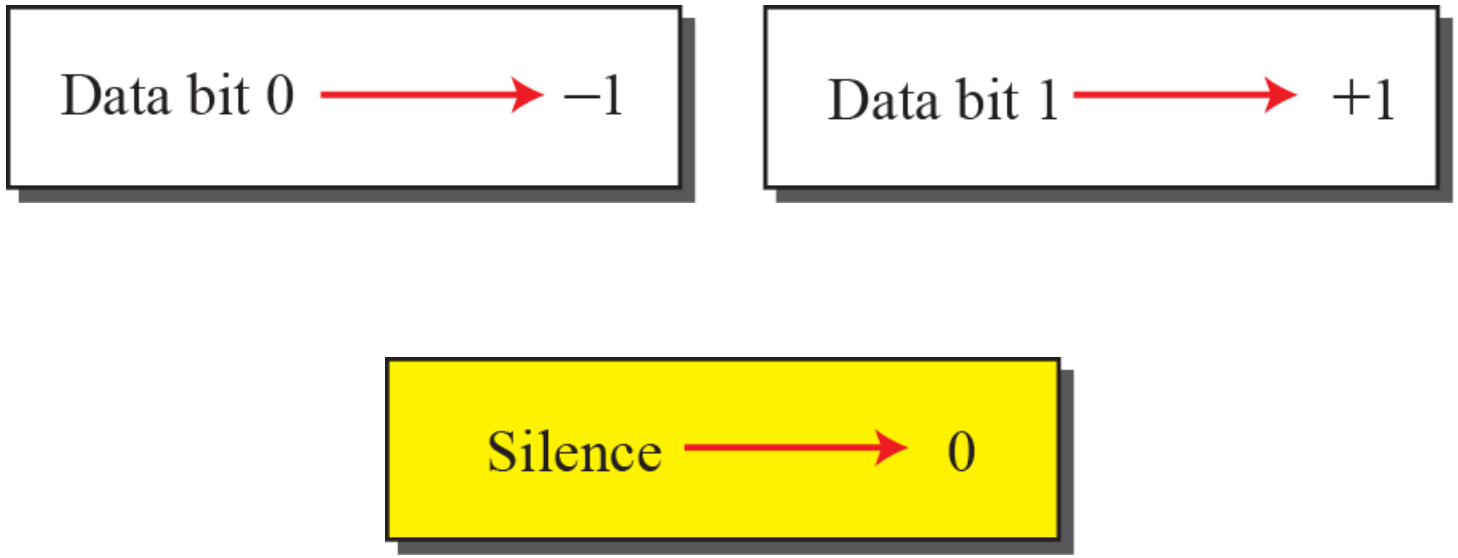


Figure 12.26: Sharing channel in CDMA

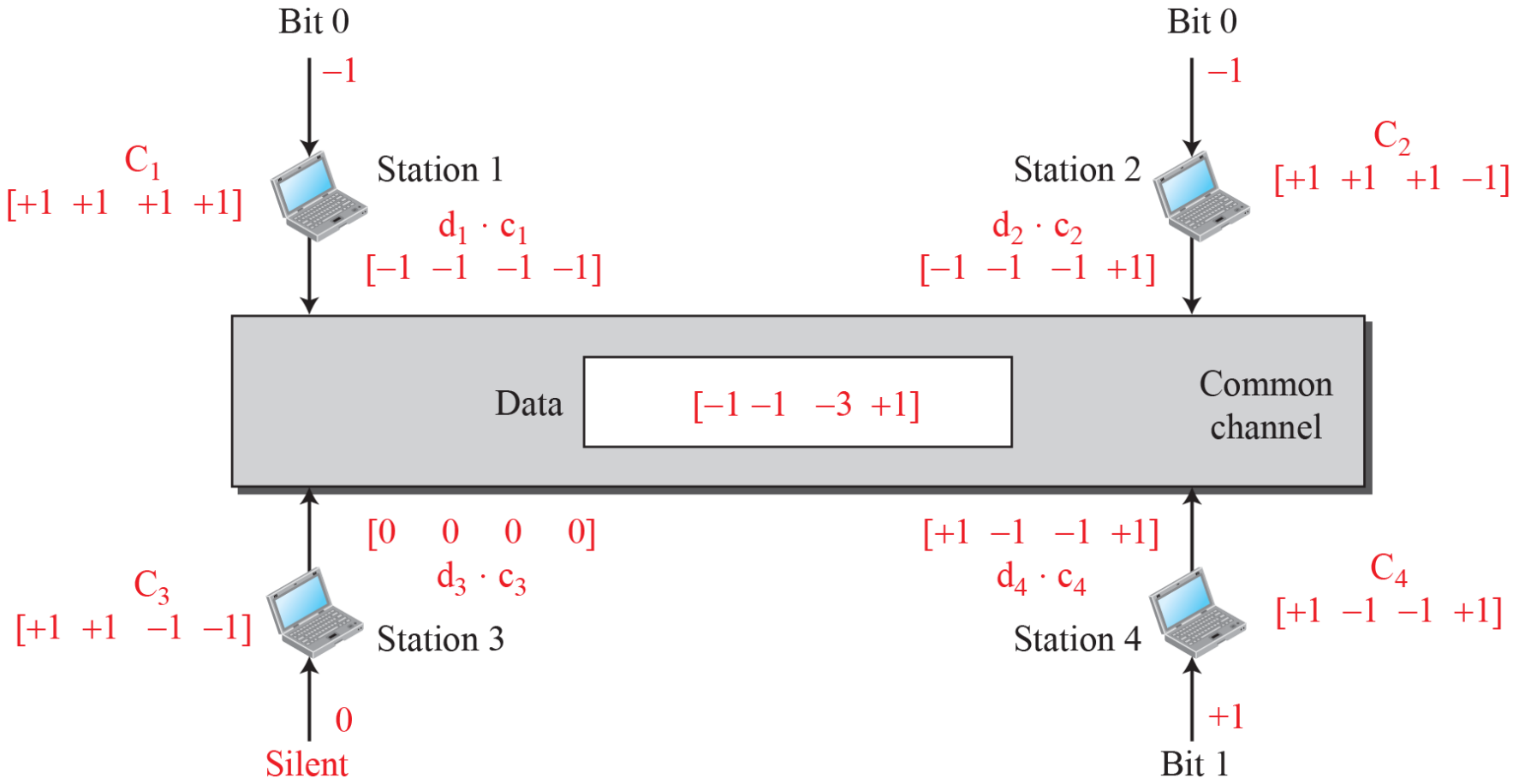


Figure 12.27: Digital signal created by four stations in CDMA

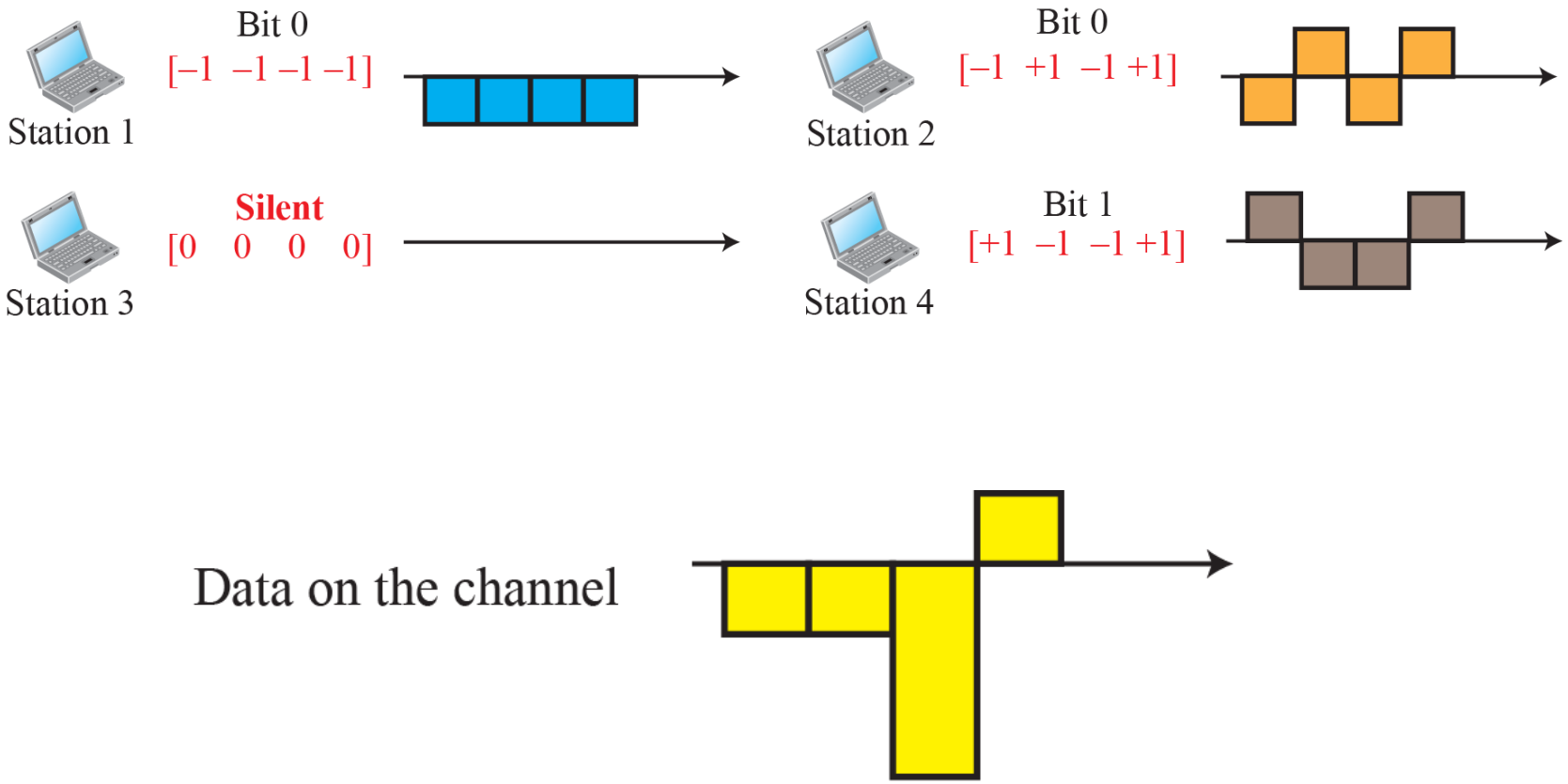


Figure 12.28: Decoding of the composite signal for one in CDMA

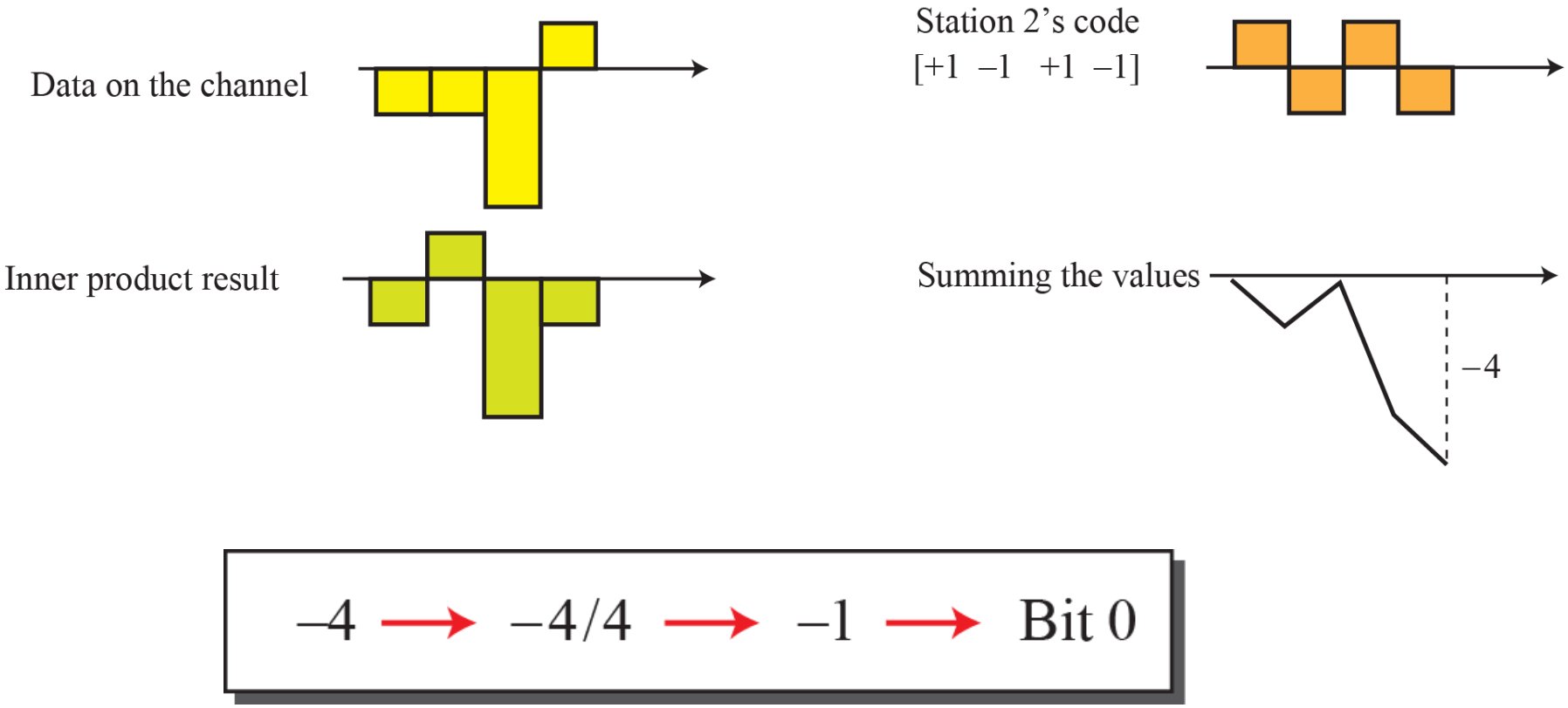


Figure 12.29: General rules and examples of creating Walsh tables

$$W_1 = [+1] \qquad W_{2N} = \begin{bmatrix} W_N & W_N \\ W_N & \overline{W_N} \end{bmatrix}$$

a. Two basic rules

$$W_2 = \begin{bmatrix} +1 & +1 \\ +1 & -1 \end{bmatrix} \qquad W_4 = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix}$$

b. Generation of W_1, W_2, and W_4

Example 12.6

Find the chips for a network with

a. Two stations

b. Four stations

Solution

We can use the rows of W_2 and W_4 in Figure 6.34:

a. For a two-station network, we have [+1 +1] and [+1 −1].

b. For a four-station network we have [+1 +1 +1 +1], [+1 −1 +1 −1], [+1 +1 −1 −1], and [+1 −1 −1 +1].

Example 12. 7

What is the number of sequences if we have 90 stations in our network?

Solution

The number of sequences needs to be 2^m. We need to choose $m = 7$ and $N = 2^7$ or 128. We can then use 90 of the sequences as the chips.

Example 12.8

Prove that a receiving station can get the data sent by a specific sender if it multiplies the entire data on the channel by the sender's chip code and then divides it by the number of stations.

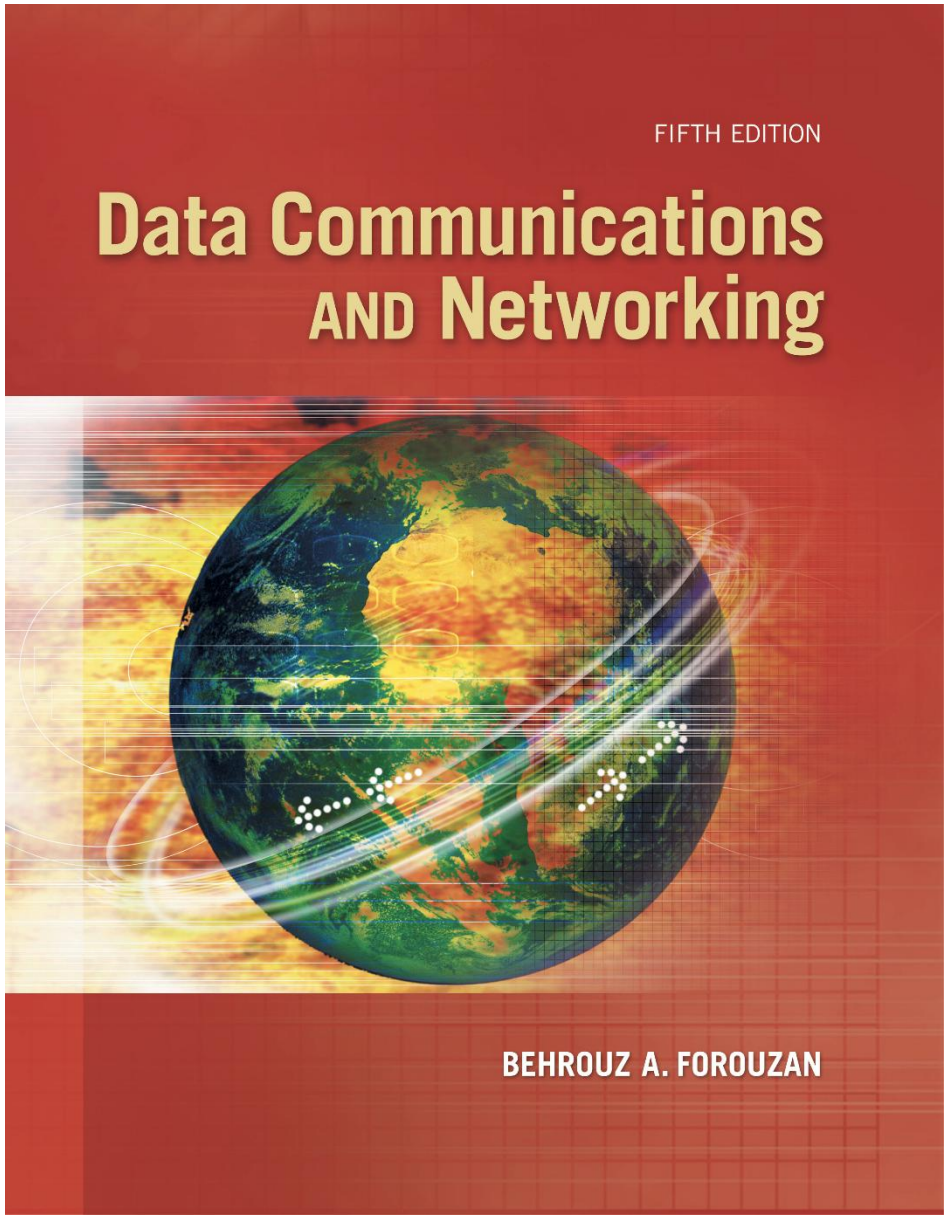
Solution

Let us prove this for the first station, using our previous four-station example. We can say that the data on the channel $D = (d_1 \cdot c_1 + d_2 \cdot c_2 + d_3 \cdot c_3 + d_4 \cdot c_4)$. The receiver, which wants to get the data sent by station 1, multiplies these data by c_1.

$$
\begin{aligned}
[D \cdot c_1] / 4 &= [(d_1 \cdot c_1 + d_2 \cdot c_2 + d_3 \cdot c_3 + d_4 \cdot c_4) \cdot c_1] / 4 \\
&= [d_1 \cdot c_1 \cdot c_1 + d_2 \cdot c_2 \cdot c_1 + d_3 \cdot c_3 \cdot c_1 + d_4 \cdot c_4 \cdot c_1] / 4 \\
&= [d_1 \times 4 + d_2 \times 0 + d_3 \times 0 + d_4 \times 0] / 4 = [d_1 \times 4] / 4 = d_1
\end{aligned}
$$

Chapter 13

Wired LANs: Ethernet



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Chapter 5: Outline

13.1 ETHERNET PROTOCOL

13.2 STANDARD ETHERNET

13.3 FAST ETHERNET

13.4 GIGABIT ETHERNET

13.5 10 GIGABIT ETHERNET

Chapter 13: Objective

- *The first section discusses the Ethernet protocol in general. It explains that IEEE Project 802 defines the LLC and MAC sub-layers for all LANs including Ethernet. The section also lists the four generations of Ethernet.*

- *The second section discusses the Standard Ethernet. The section first describes some characteristics of the Standard Ethernet. It then discusses the addressing mechanism, which is the same in all Ethernet generations. The section next discusses the access method, CSMA/ CD, which we discussed in Chapter 12. The section then reviews the efficiency of the Standard Ethernet. It then shows the encoding and the implementation of this generation.*

Chapter 13: Objective (continued)

- *The third section describes the Fast Ethernet, the second generation, which can still be seen in many places. The section first describes the changes in the MAC sublayer. The section then discusses the physical layer and the implementation of this generation.*

- *The fourth section discusses the Gigabit Ethernet, with the rate of 1 gigabit per second. The section first describes the MAC sublayer. It then moves to the physical layer and implementation.*

- *The fifth section touches on the 10 Gigabit Ethernet. This is a new technology that can be used both for a backbone LAN or as a MAN (metropolitan area network).*

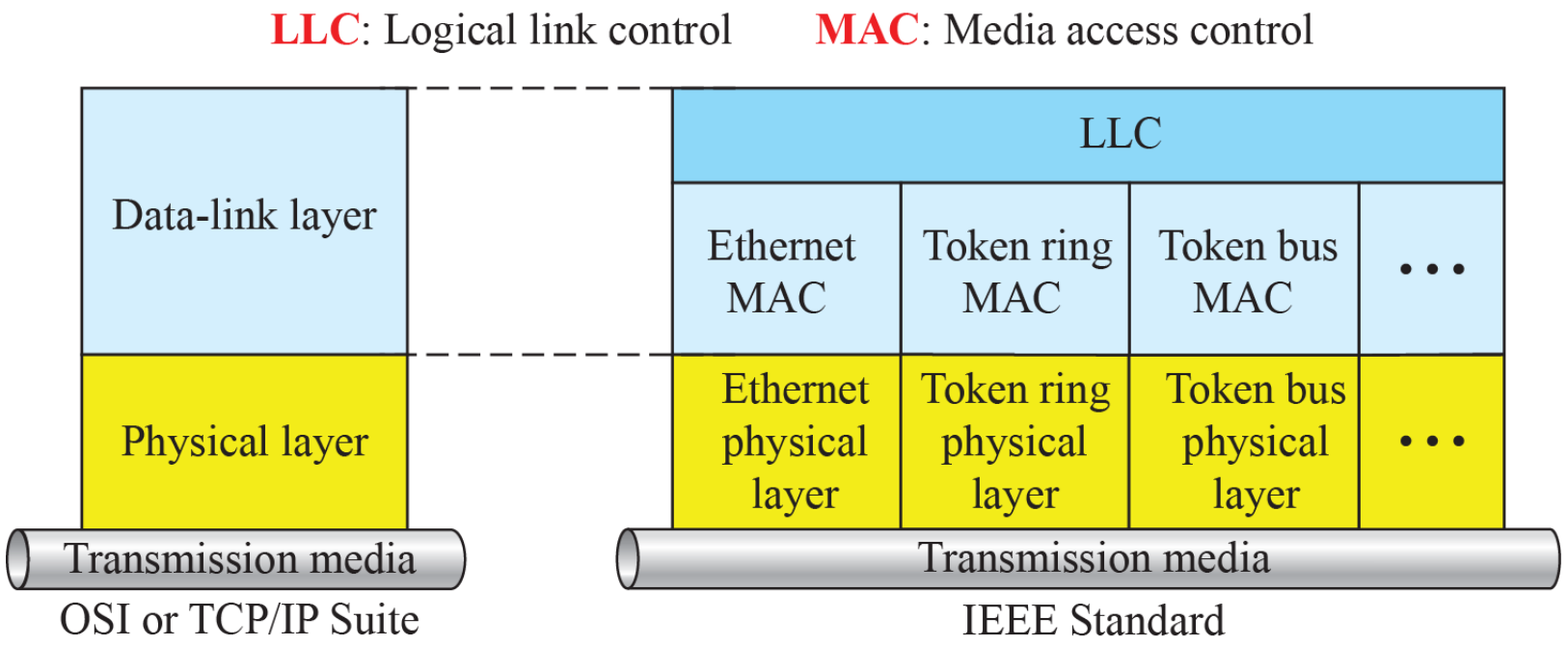
13-1 ETHERNET PROTOCOL

The data-link layer and the physical layer are the territory of the local and wide area networks. This means that when we discuss these two layers, we are talking about networks that are using them. As we see in this and the following two chapters, we can have wired or wireless networks. We discuss wired networks in this chapter and the next.

13.13.1 IEEE Project 802

In 1985, the Computer Society of the IEEE started a project, called Project 802, to set standards to enable intercommunication among equipment from a variety of manufacturers. Project 802 does not seek to replace any part of the OSI model or TCP/IP protocol suite. Instead, it is a way of specifying functions of the physical layer and the data-link layer of major LAN protocols. The relationship of the 802 Standard to the TCP/IP protocol suite is shown in Figure 13.13.

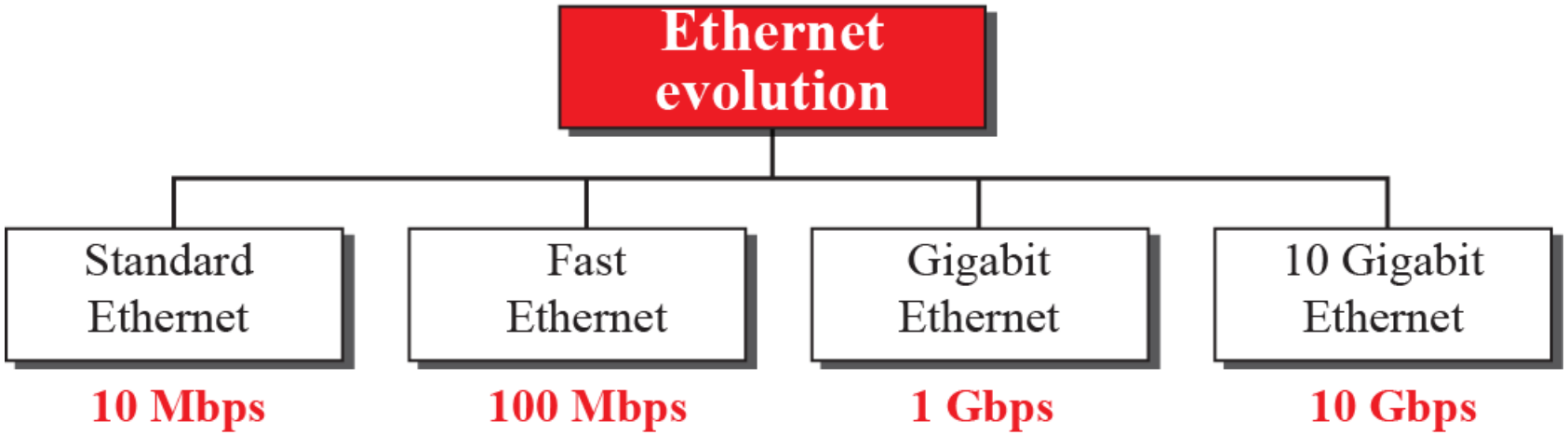
Figure 13.1: IEEE standard for LANs



13.13.2 Ethernet Evolution

The Ethernet LAN was developed in the 1970s by Robert Metcalfe and David Boggs. Since then, it has gone through four generations: Standard Ethernet (10 Mbps), Fast Ethernet (100 Mbps), Gigabit Ethernet (1 Gbps), and 10 Gigabit Ethernet (10 Gbps), as shown in Figure 13.2. We briefly discuss all these generations.

Figure 13.2 : Ethernet evolution



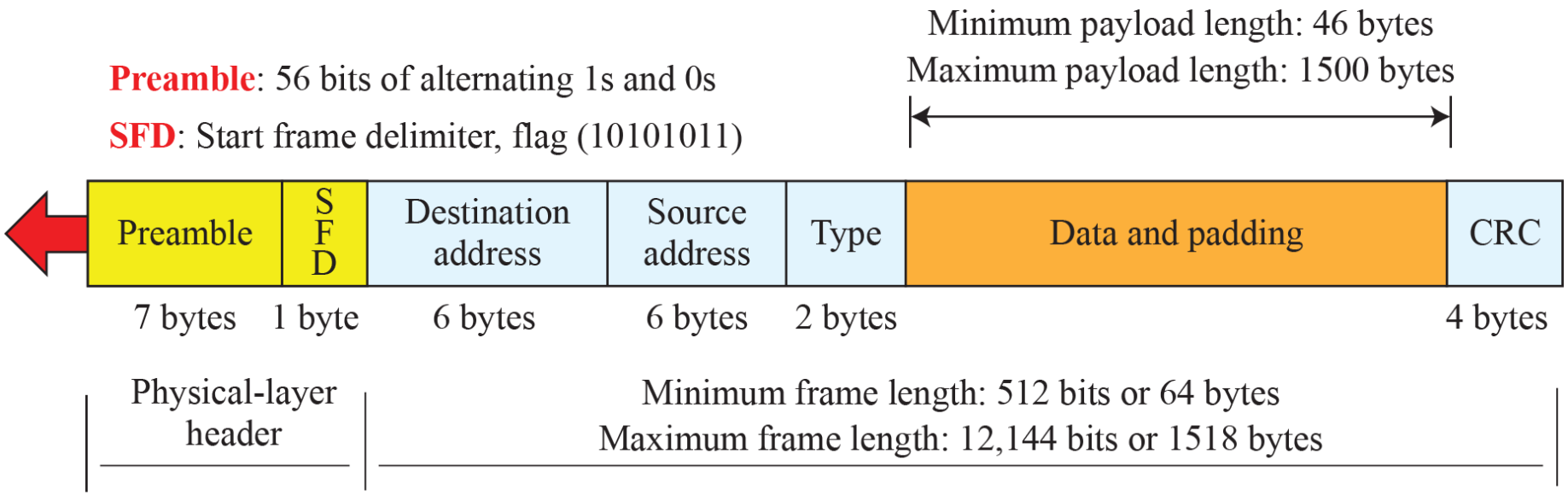
13-2 STANDARD ETHERNET

We refer to the original Ethernet technology with the data rate of 10 Mbps as the Standard Ethernet. Although most implementations have moved to other technologies in the Ethernet evolution, there are some features of the Standard Ethernet that have not changed during the evolution. We discuss this standard version first.

13.2.1 Characteristics

Let us first discuss some characteristics of the Standard Ethernet.

Figure 13.3: Ethernet frame



Example 13.1

Show how the address 47:20:1B:2E:08:EE is sent out online.

Solution

The address is sent left to right, byte by byte; for each byte, it is sent right to left, bit by bit, as shown below:

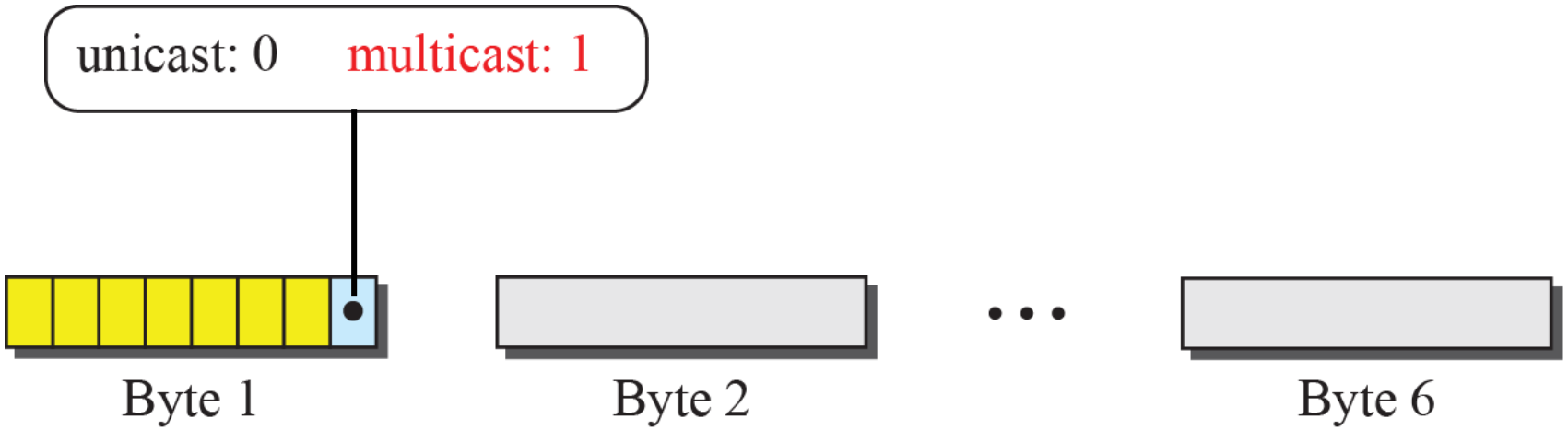
Hexadecimal	47	20	1B	2E	08	EE
Binarys	01000111	00100000	00011011	00101110	00001000	11101110
Transmitted ←	11100010	00000100	11011000	01110100	00010000	01110111

13.2.2 Addressing

Each station on an Ethernet network (such as a PC, workstation, or printer) has its own network interface card (NIC). The NIC fits inside the station and provides the station with a link-layer address. The Ethernet address is 6 bytes (48 bits), normally written in hexadecimal notation, with a colon between the bytes. For example, the following shows an Ethernet MAC address:

4A:30:10:21:10:1A

Figure 13.4: Unicast and multicast addresses



Example 13.2

Define the type of the following destination addresses:

a. 4A:30:10:21:10:1A

b. 47:20:1B:2E:08:EE

c. FF:FF:FF:FF:FF:FF

Solution

To find the type of the address, we need to look at the second hexadecimal digit from the left. If it is even, the address is unicast. If it is odd, the address is multicast. If all digits are Fs, the address is broadcast. Therefore, we have the following:

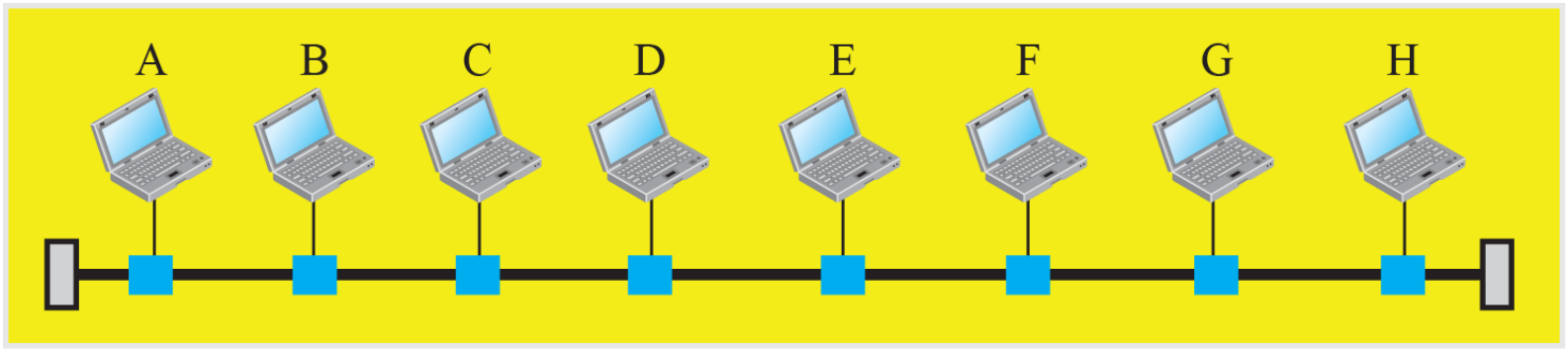
Example 13.2 (continued)

a. This is a unicast address because A in binary is 1010 (even).

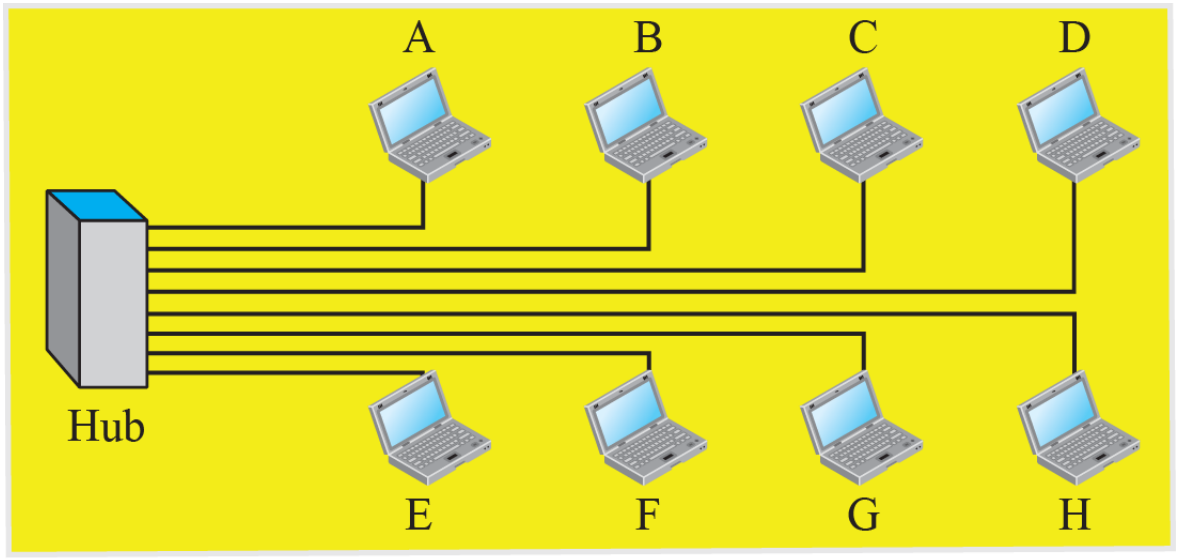
b. This is a multicast address because 7 in binary is 0111 (odd).

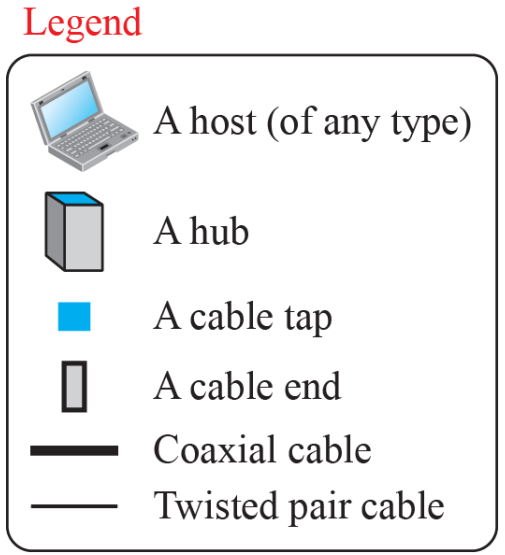
c. This is a broadcast address because all digits are Fs in hexadecimal.

Figure 13.5: Implementation of standard Ethernet



a. A LAN with a bus topology using a coaxial cable





b. A LAN with a star topology using a hub

13.2.3 Access Method

Since the network that uses the standard Ethernet protocol is a broadcast network, we need to use an access method to control access to the sharing medium. The standard Ethernet chose CSMA/CD with 1-persistent method, discussed earlier in Chapter 12, Section 13.3. Let us use a scenario to see how this method works for the Ethernet protocol.

13.2.4 Efficiency of Standard Ethernet

The efficiency of the Ethernet is defined as the ratio of the time used by a station to send data to the time the medium is occupied by this station. The practical efficiency of standard Ethernet has been measured to be

$$\text{Efficiency} = 1 / (1 + 6.4 \times a)$$

Example 13.3

In the Standard Ethernet with the transmission rate of 10 Mbps, we assume that the length of the medium is 2500 m and the size of the frame is 512 bits. The propagation speed of a signal in a cable is normally 2×10^8 m/s.

Propagation delay = $2500/(2 \times 10^8) = 12.5$ µs Transmission delay = $512/(10^7) = 51.2$ µs

$a = 12.5/51.2 = 0.24$ Efficiency = 39%

The example shows that a = 0.24, which means only 0.24 of a frame occupies the whole medium in this case. The efficiency is 39 percent, which is considered moderate; it means that only 61 percent of the time the medium is occupied but not used by a station.

13.2.5 Implementation

The Standard Ethernet defined several implementations, but only four of them became popular during the 1980s. Table 13.1 shows a summary of Standard Ethernet implementations.

Table 13.1: Summary of Standard Ethernet implementations

Implementation	*Medium*	*Medium Length*	*Encoding*
10Base5	Thick coax	500 m	Manchester
10Base2	Thin coax	185 m	Manchester
10Base-T	2 UTP	100 m	Manchester
10Base-F	2 Fiber	2000	Manchester

Figure 13.6: Encoding in a Standard Ethernet

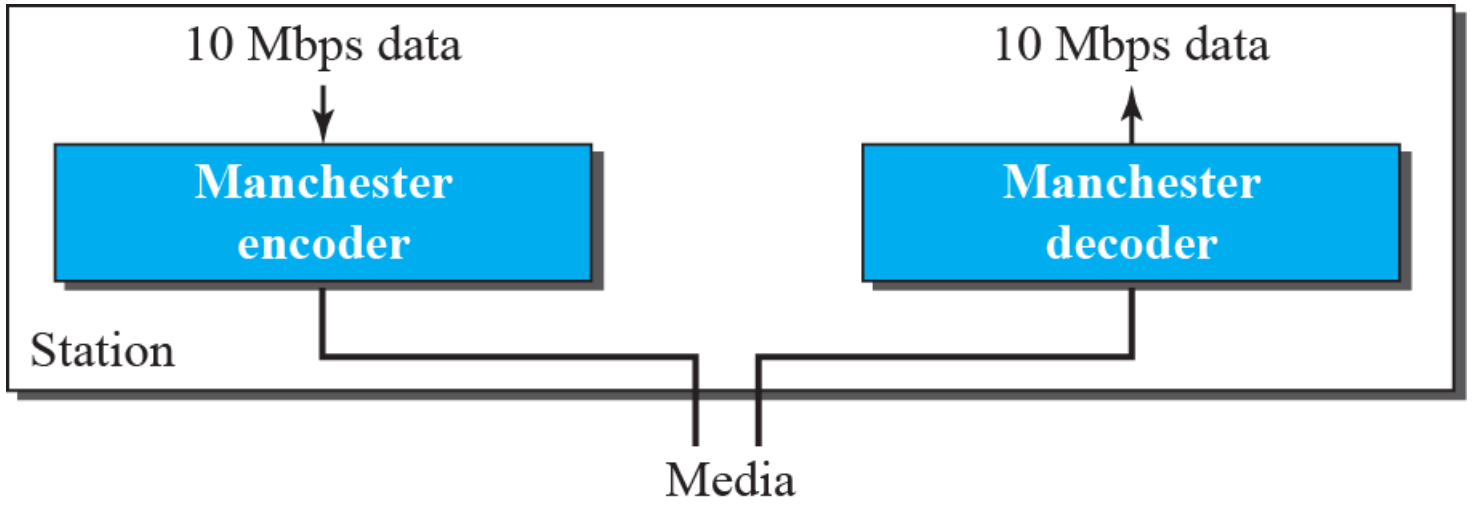


Figure 13.7: 10Base5 implementation

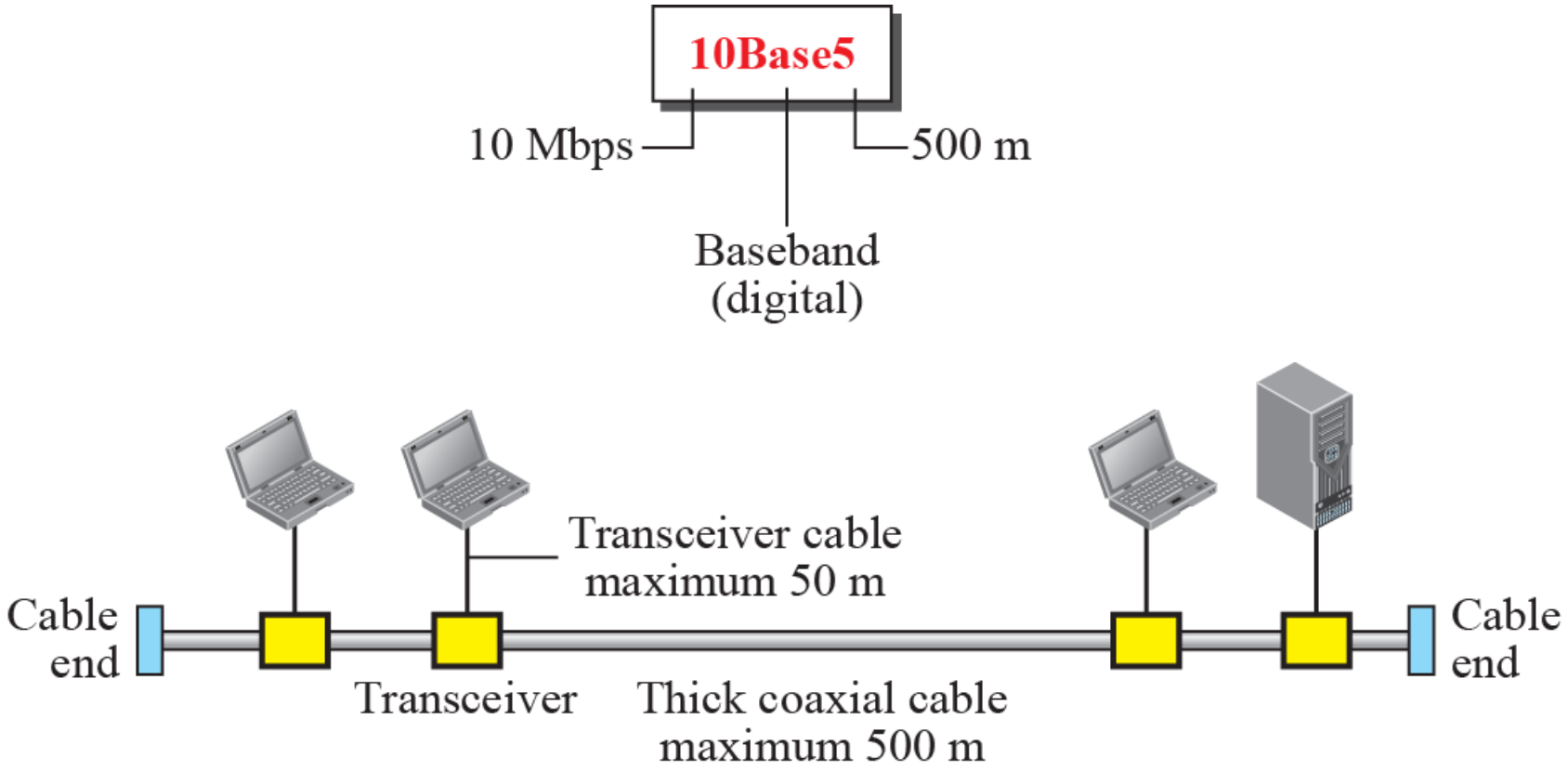


Figure 13.8: 10Base2 implementation

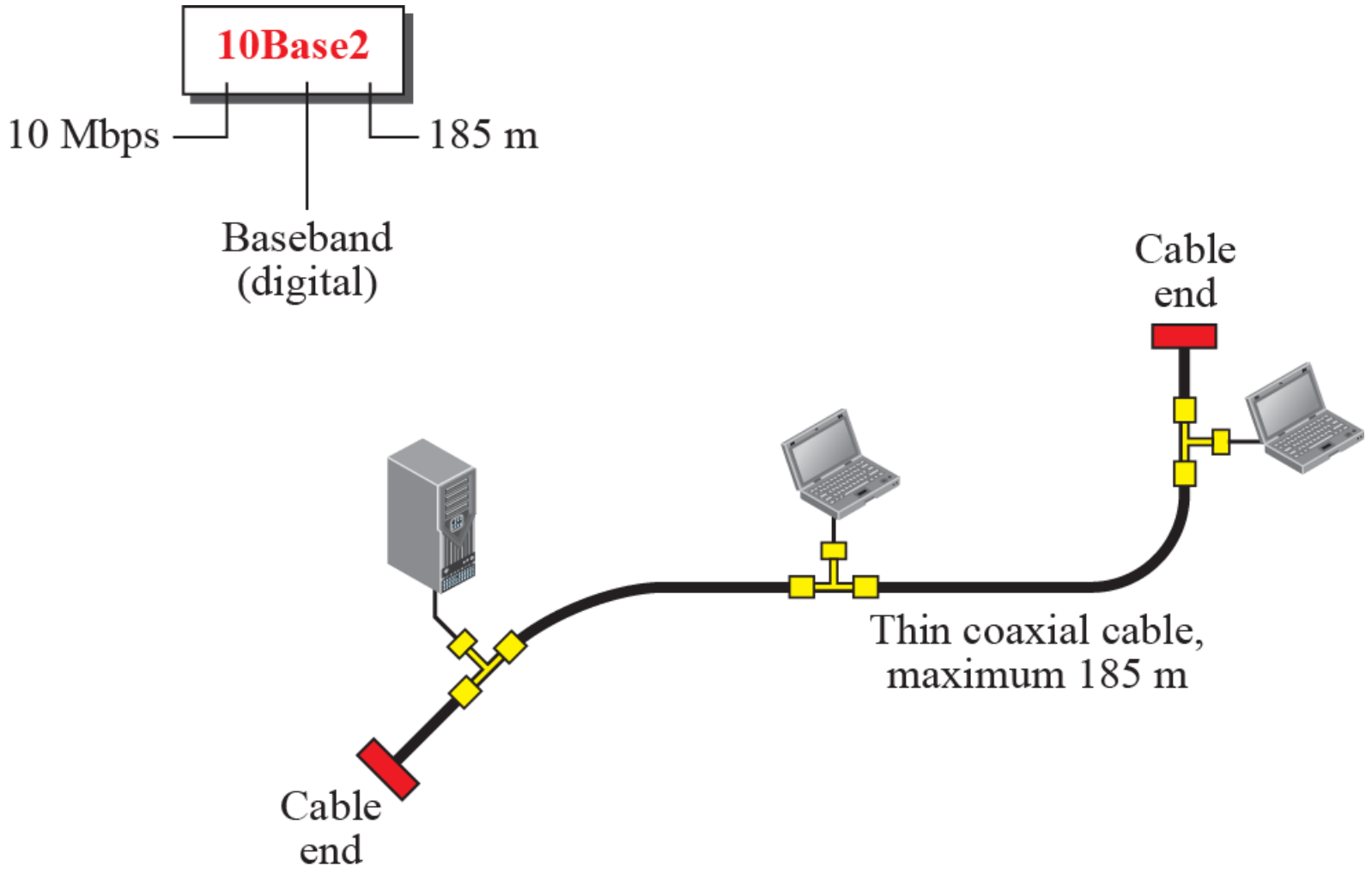


Figure 13.9: 10Base-T implementation

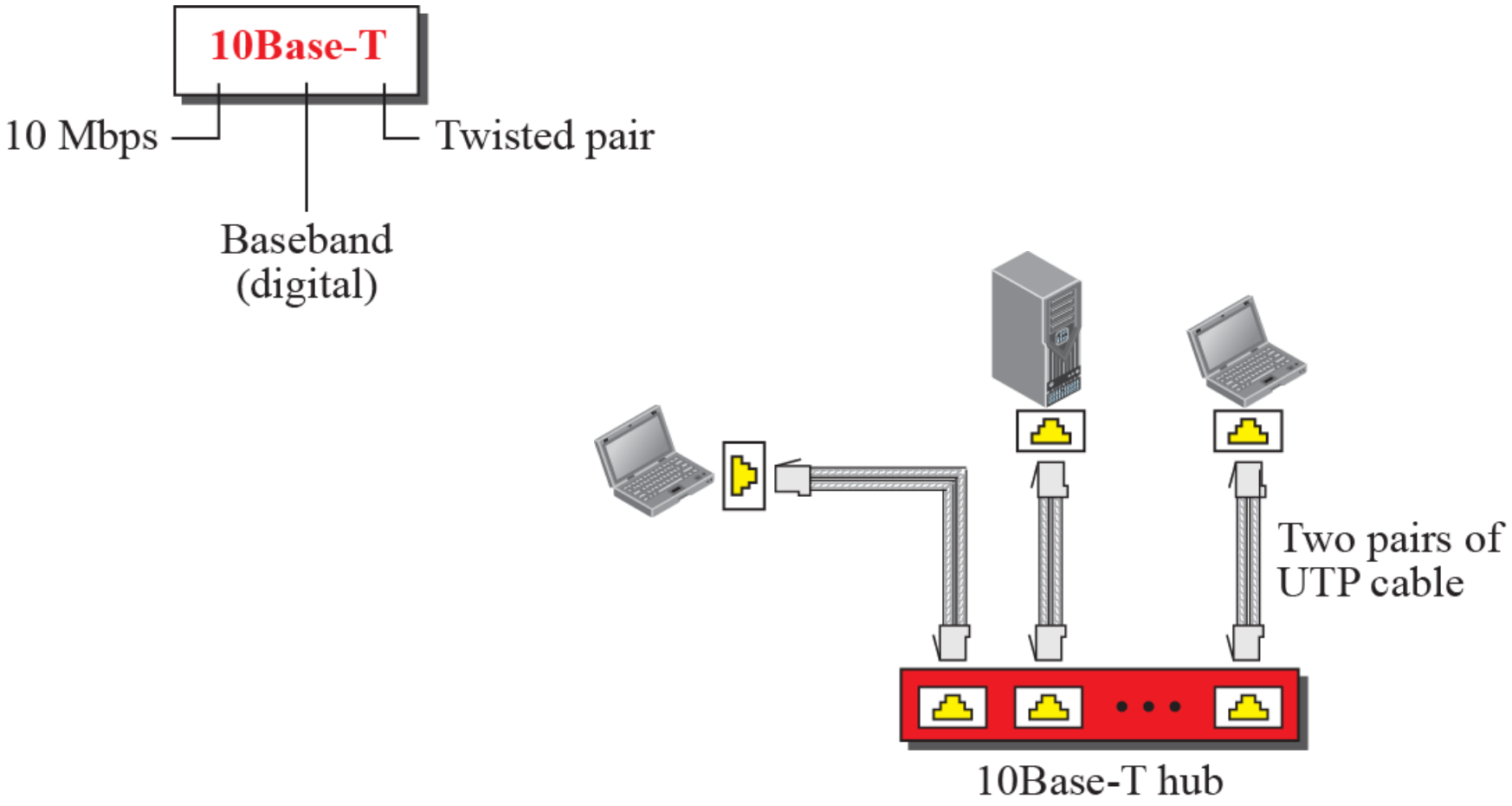
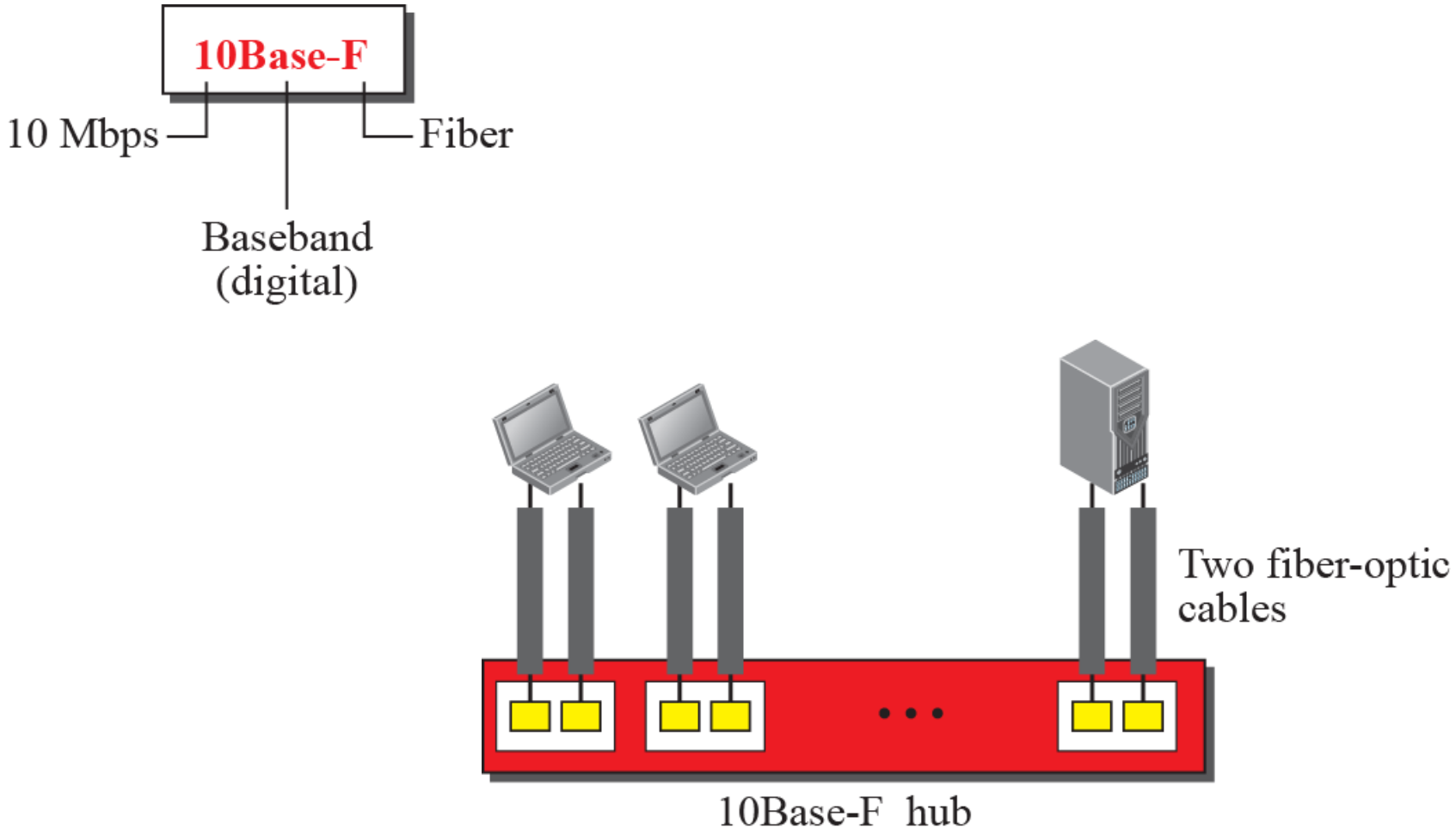


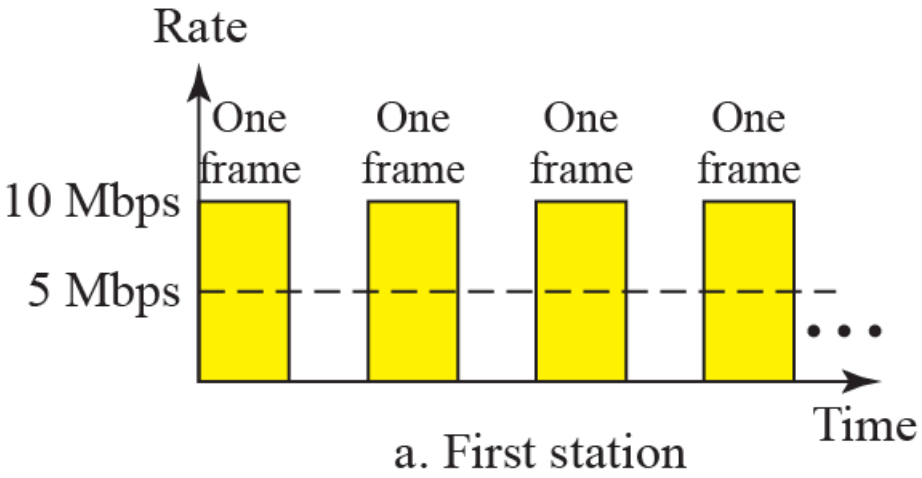
Figure 13.10: 10Base-F implementation



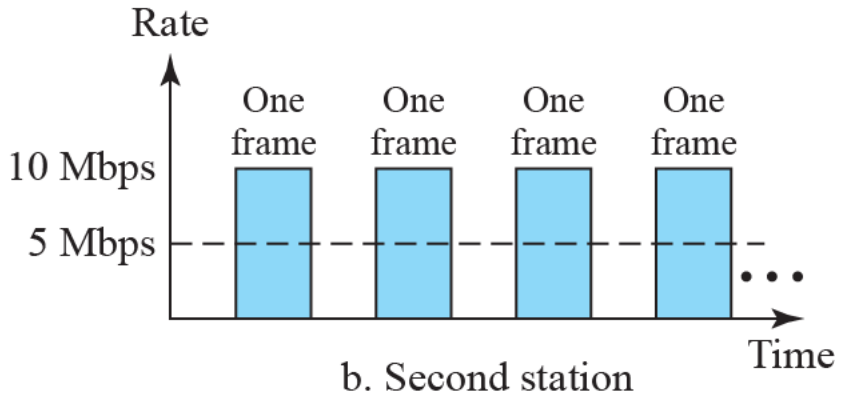
13.2.6 Changes in the Standard

Before we discuss higher-rate Ethernet protocols, we need to discuss the changes that occurred to the 10-Mbps Standard Ethernet. These changes actually opened the road to the evolution of the Ethernet to become compatible with other high-data-rate LANs.

Figure 13.11: Sharing bandwidth



a. First station

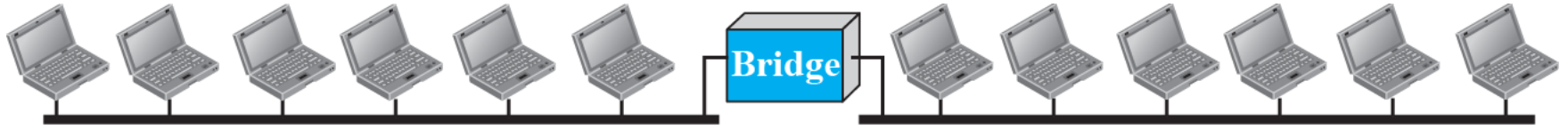


b. Second station

Figure 13.12: A network with and without bridging

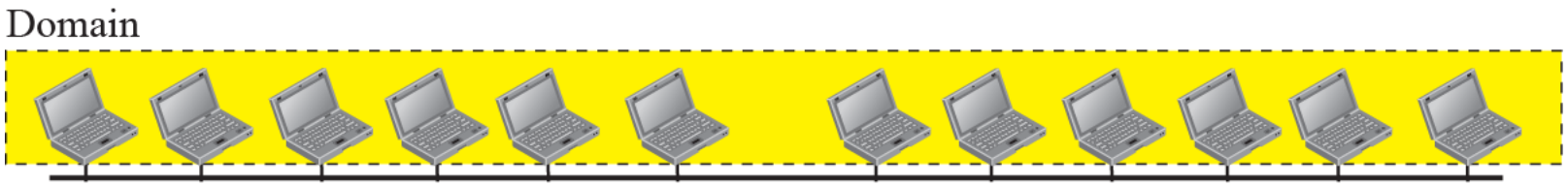


a. Without bridging

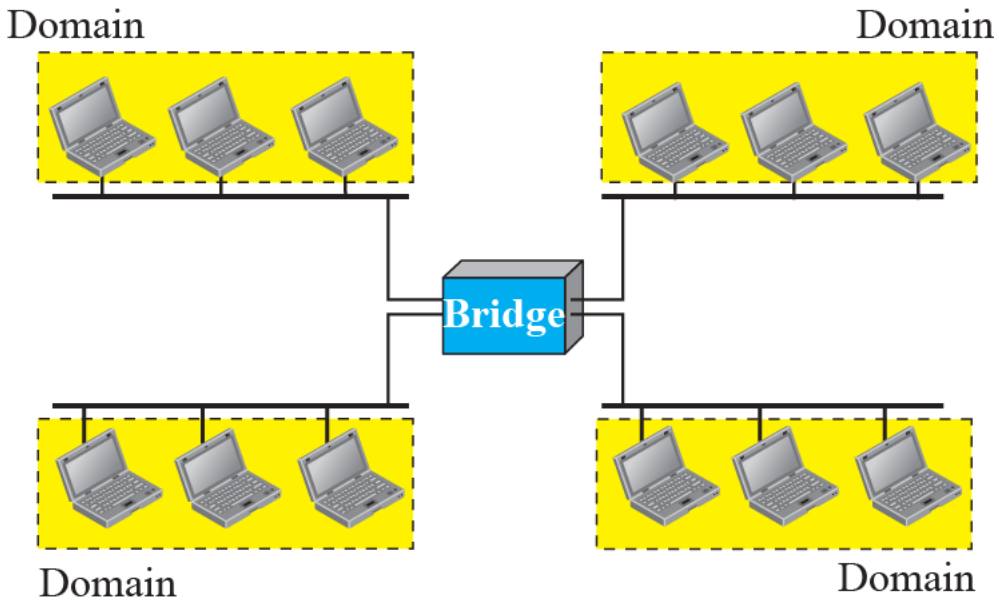


b. With bridging

Figure 13.13: Collision domains



a. Without bridging



b. With bridging

Figure 13.14: Switched Ethernet

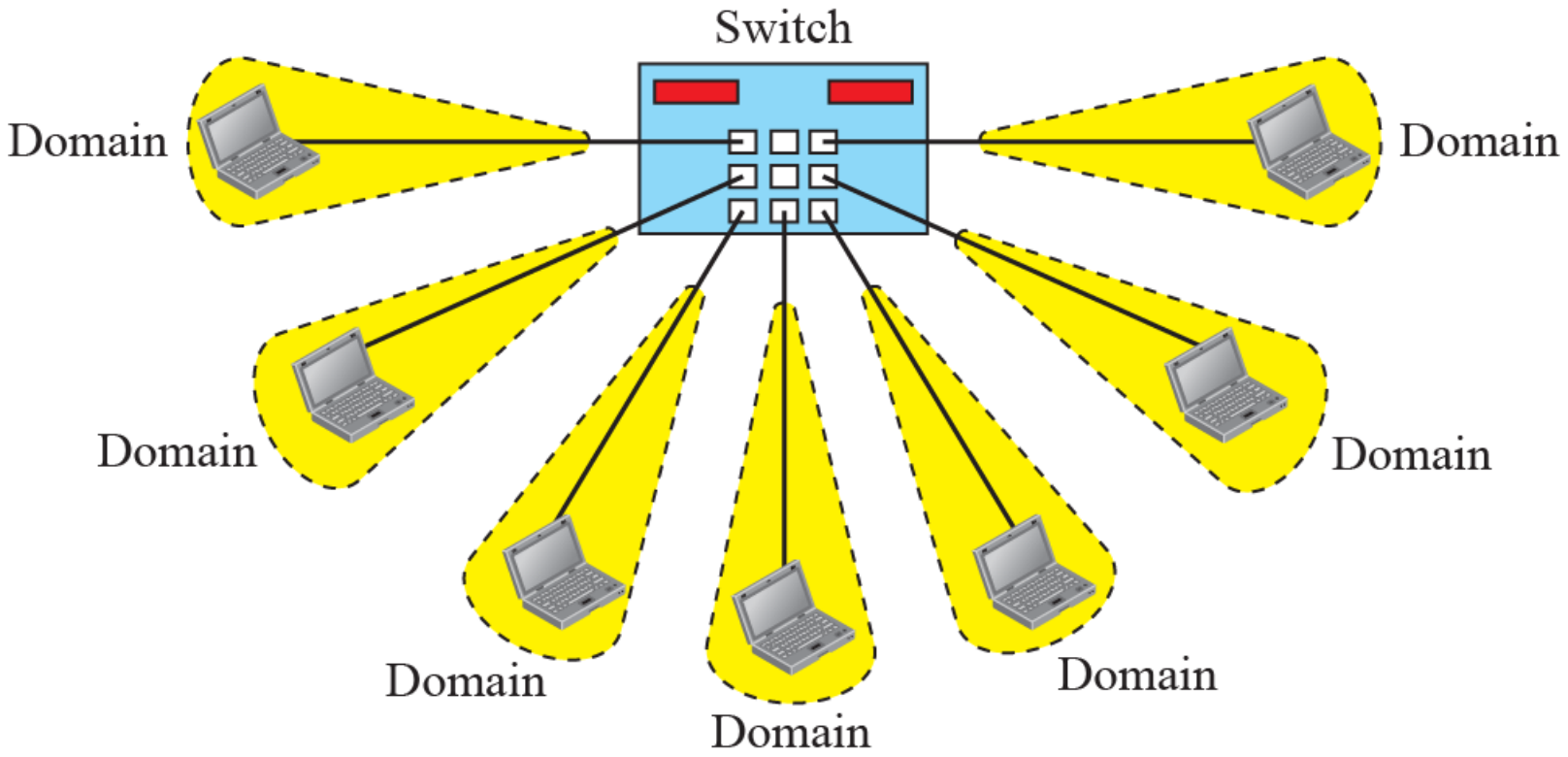
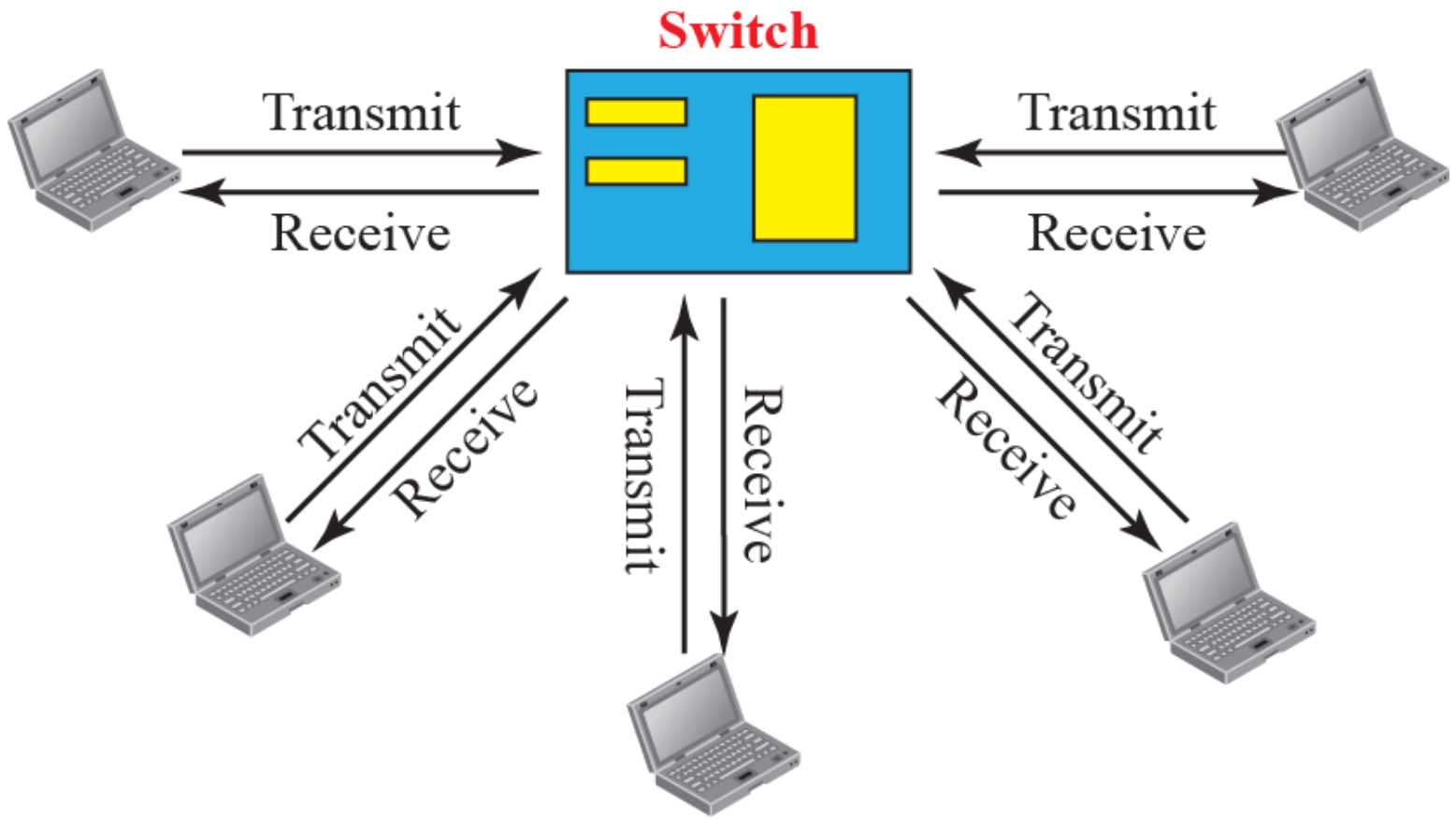


Figure 13.15: Full – duplex switched Ethernet



13-3 FAST ETHERNET

In the 1990s, Ethernet made a big jump by increasing the transmission rate to 100 Mbps, and the new generation was called the Fast Ethernet. The designers of the Fast Ethernet needed to make it compatible with the Standard Ethernet. The MAC sublayer was left unchanged. But the features of the Standard Ethernet that depend on the transmission rate, had to be changed.

13.3.1 Access Method

We remember that the proper operation of the CSMA/CD depends on the transmission rate, the minimum size of the frame, and the maximum network length. If we want to keep the minimum size of the frame, the maximum length of the network should be changed. In other words, if the minimum frame size is still 512 bits, and it is transmitted 10 times faster, the collision needs to be detected 10 times sooner, which means the maximum length of the network should be 10 times shorter (the propagation speed does not change).

13.3.2 Physical Layer

To be able to handle a 100 Mbps data rate, several changes need to be made at the physical layer.

Figure 13.16: Encoding for fast Ethernet

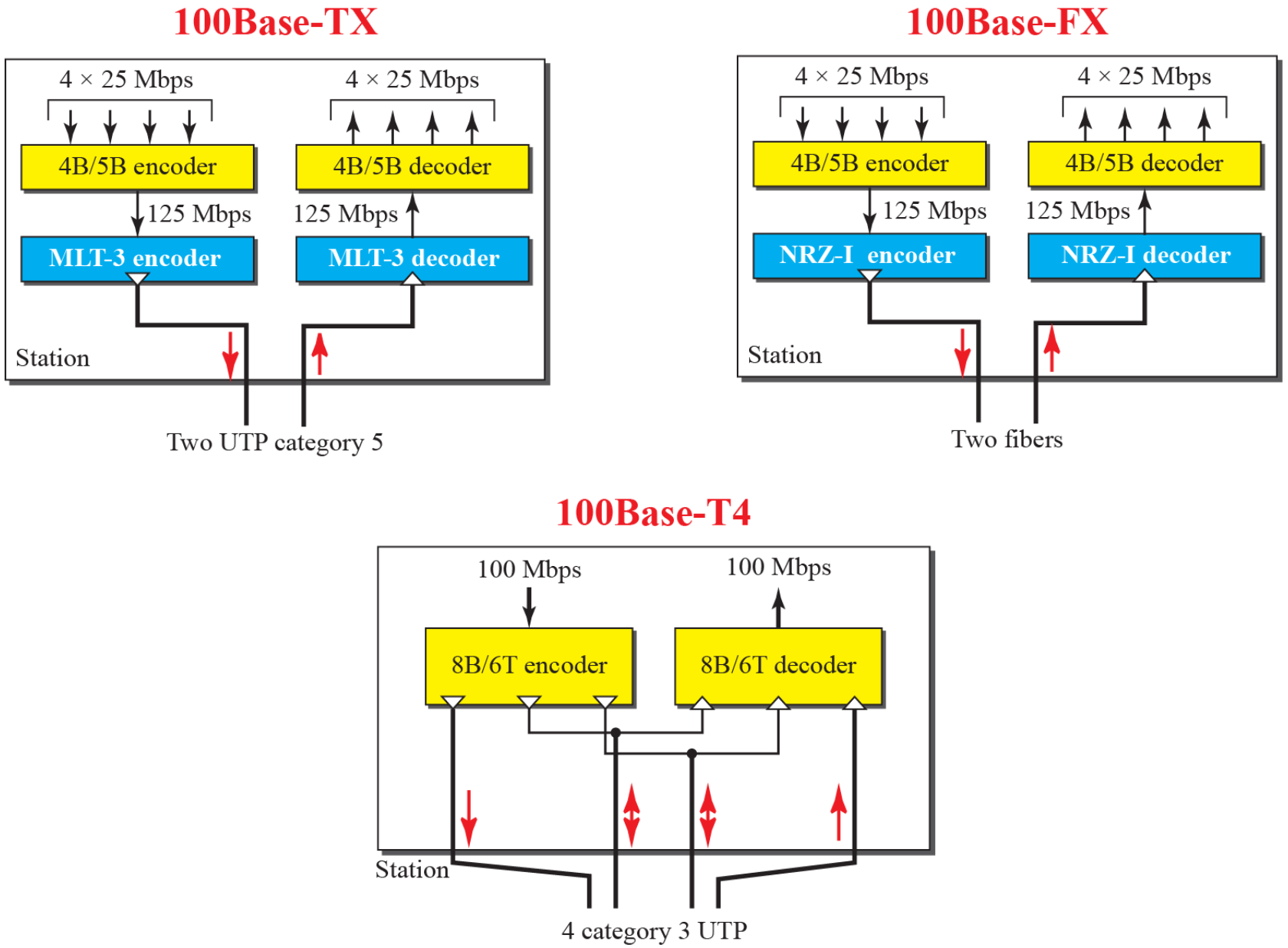


Table 13.2: Summary of Fast Ethernet implementations

Implementation	*Medium*	*Medium Length*	*Wires*	*Encoding*
100Base-TX	STP	100 m	2	4B5B + MLT-3
100Base-FX	Fiber	185 m	2	4B5B + NRZ-I
100Base-T4	UTP	100 m	4	Two 8B/6T

13-4 GIGABIT ETHERNET

The need for an even higher data rate resulted in the design of the Gigabit Ethernet Protocol (1000 Mbps). The IEEE committee calls it the Standard 802.3z. The goals of the Gigabit Ethernet were to upgrade the data rate to 1 Gbps, but keep the address length, the frame format, and the maximum and minimum frame length the same.

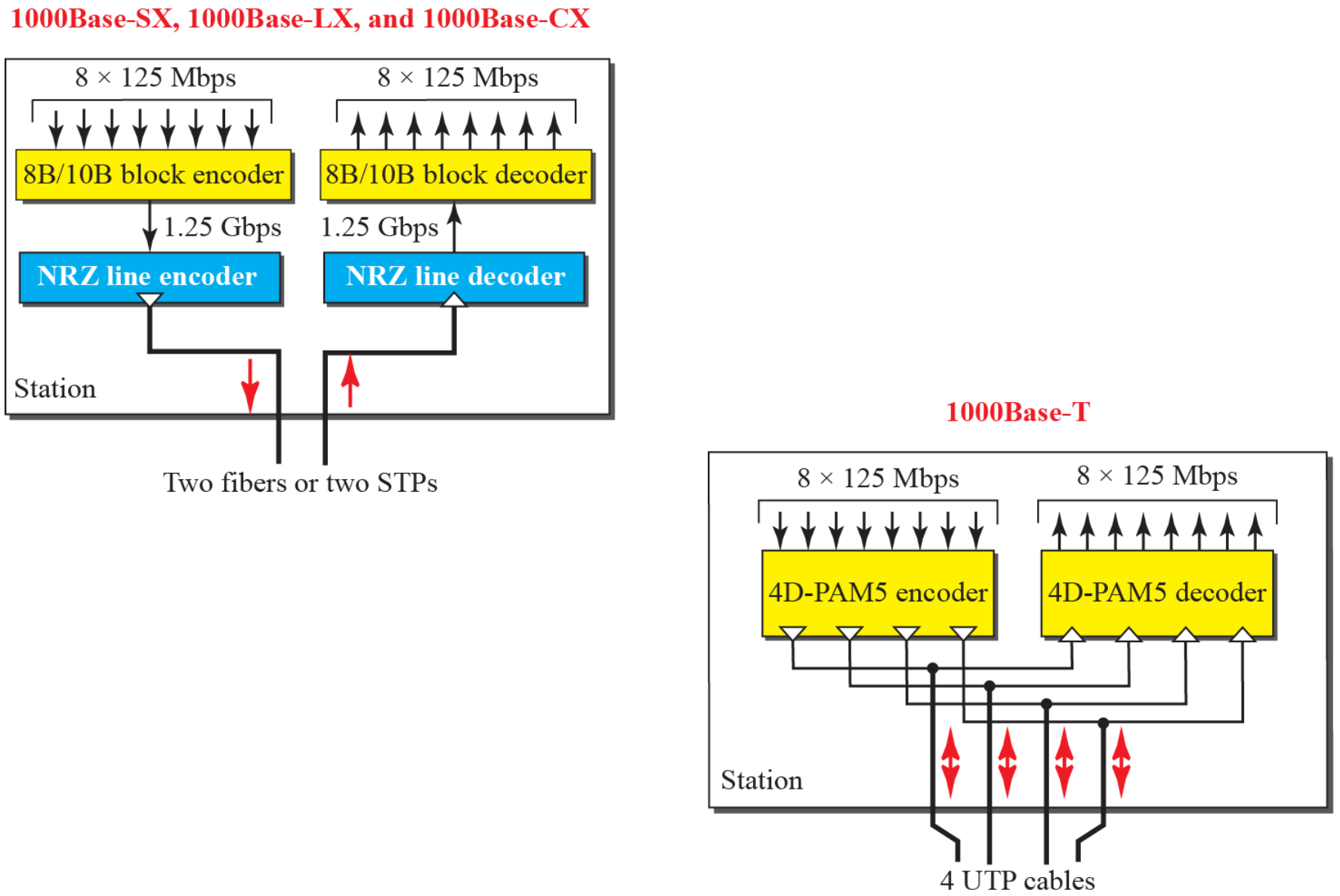
13.4.1 MAC Sublayer

A main consideration in the evolution of Ethernet was to keep the MAC sublayer untouched. However, to achieve a data rate of 1 Gbps, this was no longer possible. Gigabit Ethernet has two distinctive approaches for medium access: half-duplex and full-duplex. Almost all implementations of Gigabit Ethernet follow the full-duplex approach, so we mostly ignore the half-duplex mode.

13.4.2 Physical Layer

The physical layer in Gigabit Ethernet is more complicated than that in Standard or Fast Ethernet. We briefly discuss some features of this layer.

Figure 13.17: Encoding in Gigabit Ethernet



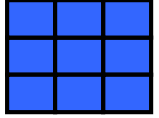


Table 13.3: Summary of Gigabit Ethernet implementations

Implementation	*Medium*	*Medium Length*	*Wires*	*Encoding*
1000Base-SX	Fiber S-W	550 m	2	8B/10B + NRZ
1000Base-LX	Fiber L-W	5000 m	2	8B/10B + NRZ
1000Base-CX	STP	25 m	2	8B/10B + NRZ
1000Base-T4	UTP	100 m	4	4D-PAM5

13-5 10-GIGABIT EHTERNET

In recent years, there has been another look into the Ethernet for use in metropolitan areas. The idea is to extend the technology, the data rate, and the coverage distance so that the Ethernet can be used as LAN and MAN (metropolitan area network). The IEEE committee created 10 Gigabit Ethernet and called it Standard 802.3ae.

13.5.1 Implementation

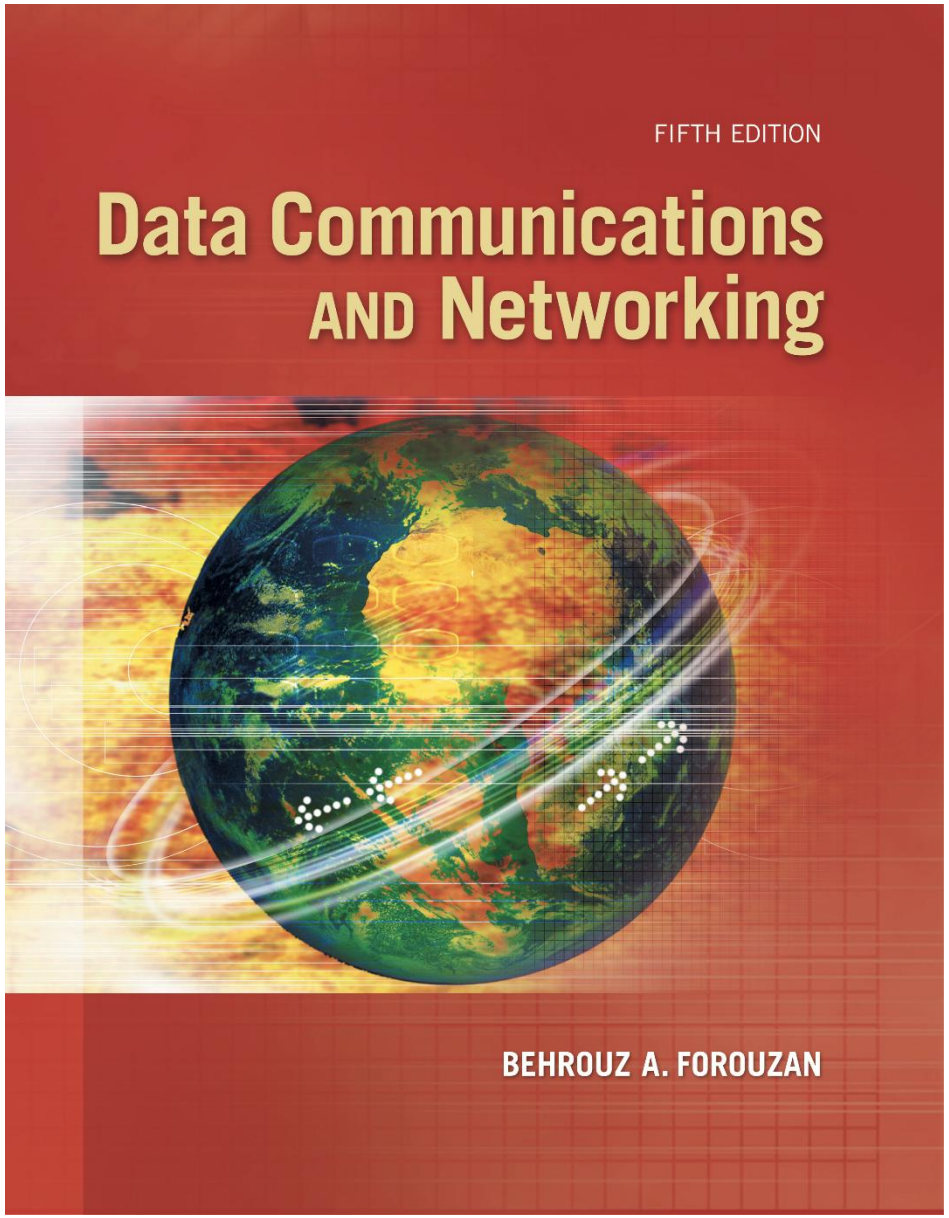
10 Gigabit Ethernet operates only in full-duplex mode, which means there is no need for contention; CSMA/CD is not used in 10 Gigabit Ethernet. Four implementations are the most common: 10GBase-SR, 10GBase-LR, 10GBase-EW, and 10GBase-X4. Table 13.4 shows a summary of the 10 Gigabit Ethernet implementations. We discussed the encoding in Chapter 4.

Table 13.4: Summary of 10-Gigabit Ethernet implementations

Implementation	*Medium*	*Medium Length*	*Number of wires*	*Encoding*
10GBase-SR	Fiber 850 nm	300 m	2	64B66B
10GBase-LR	Fiber 1310 nm	10 Km	2	64B66B
10GBase-EW	Fiber 1350 nm	40 Km	2	SONET
10GBase-X4	Fiber 1310 nm	300 m to 10 Km	2	8B10B

Chapter 15

Wireless LANs



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Chapter6: Outline

15.1 INTRODUCTION

15.2 IEEE 802.11 PROJECT

15.3 BLUETOOTH

Chapter 15: Objective

- *The first section introduces the general issues behind wireless LANs and compares wired and wireless networks. The section describes the characteristics of the wireless networks and the way access is controlled in these types of networks.*
- *The second section discusses a wireless LAN defined by the IEEE 802.11 Project. This section defines the architecture of this type of LAN and describes the MAC sublayer.*
- *The third section discusses the Bluetooth technology as a personal area network (PAN). The section describes the architecture of the network, the addressing mechanism, and the packet format. Different layers used in this protocol are also briefly described and compared with the ones in the other wired and wireless LANs.*

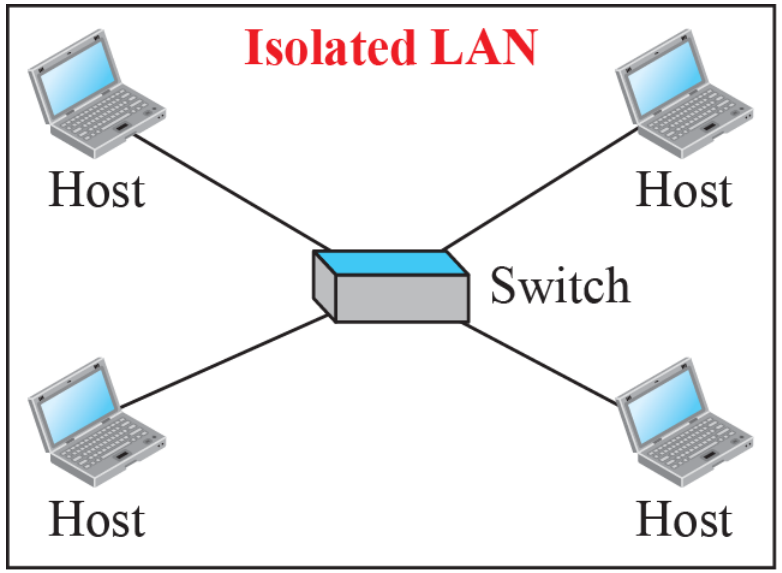
15-1 INTRODUCTION

Wireless communication is one of the fastest-growing technologies. The demand for connecting devices without the use of cables is increasing everywhere. Wireless LANs can be found on college campuses, in office buildings, and in many public areas. Before we discuss a specific protocol related to wireless LANs, let us talk about them in general.

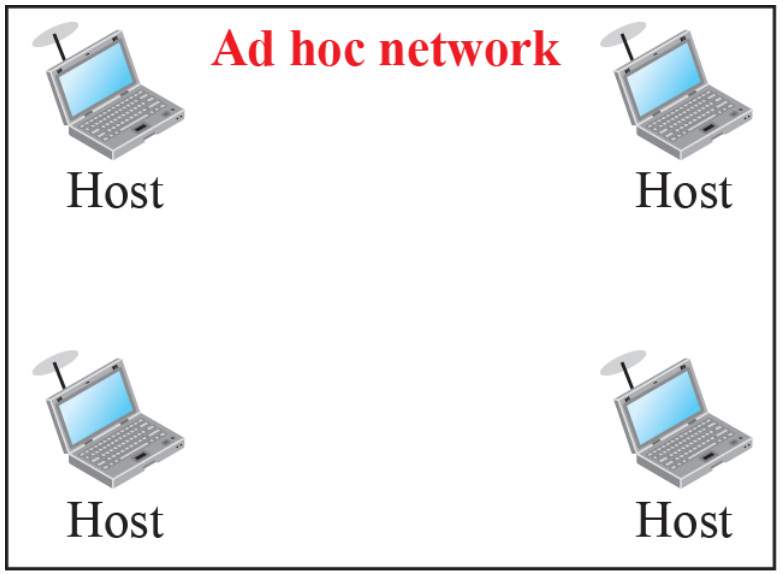
15.15.1 Architectural Comparison

Let us first compare the architecture of wired and wireless LANs to give some idea of what we need to look for when we study wireless LANs.

Figure 15.1: Isolated LANs: wired versus wireless

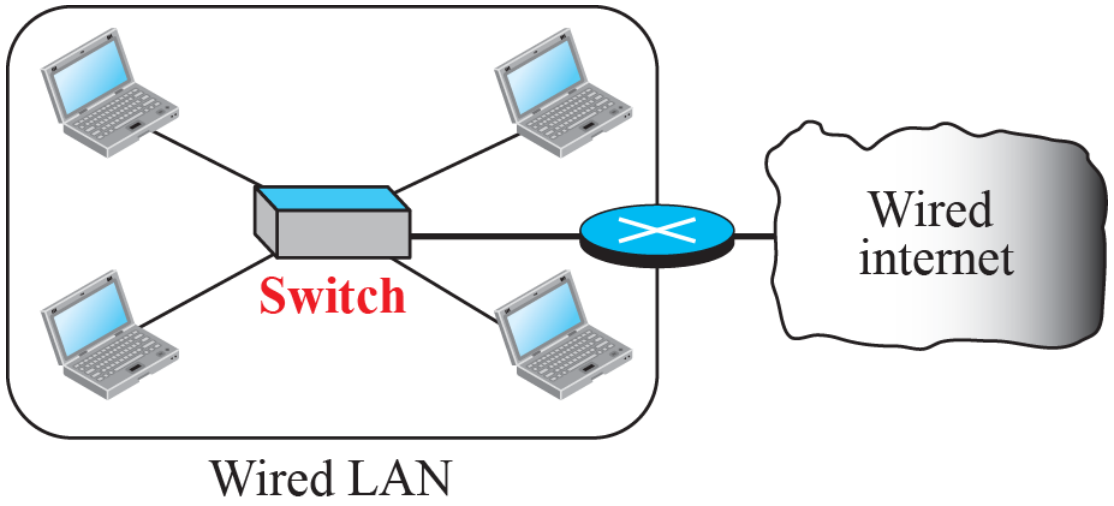


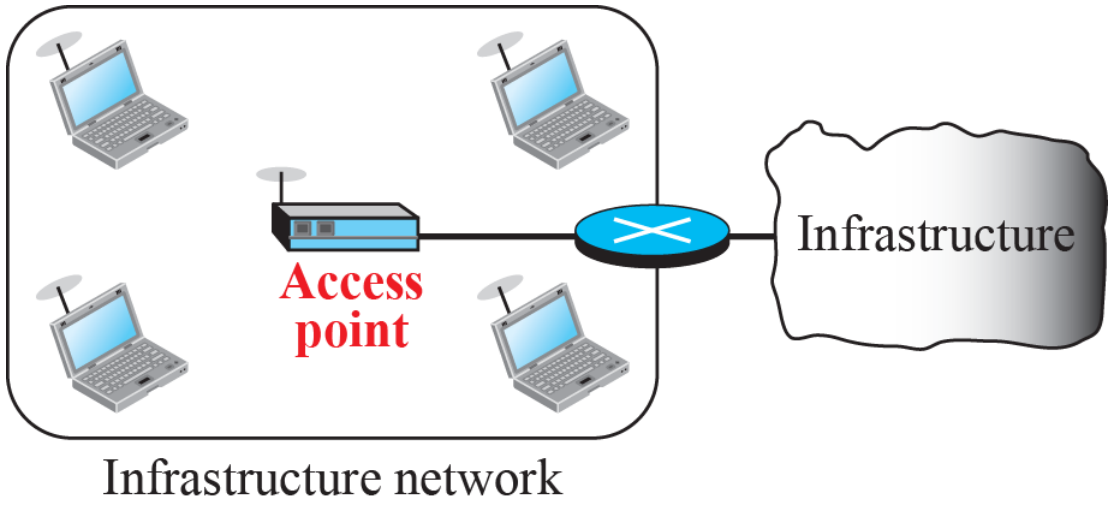
Wired



Wireless

Figure 15.2: Connection of a wired LAN and a wireless LAN to other networks





15.15.2 Characteristics

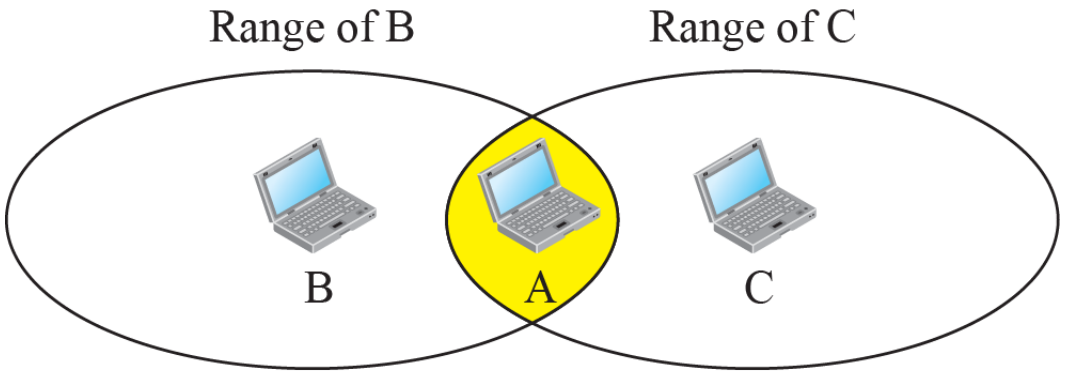
There are several characteristics of wireless LANs that either do not apply to wired LANs or the existence of which is negligible and can be ignored. We discuss some of these characteristics here to pave the way for discussing wireless LAN protocols.

15.15.3 Access Control

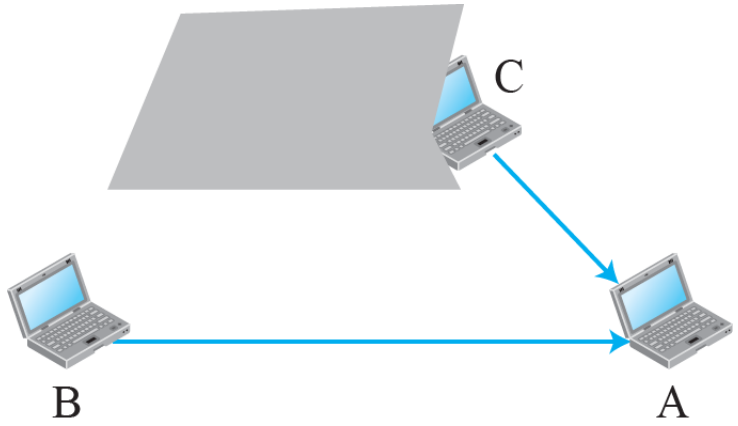
Maybe the most important issue we need to discuss in a wireless LAN is access control—how a wireless hos t can get access to the shared medium (air). The CSM A/CD algorithm does not work in wireless LANs for t hree reasons:

1. Wireless hosts do not have enough power to send and receive at the same time.
2. The hidden station problem prevents collision det ection
3. The distance between stations can be great.

Figure 15.3: Hidden station problem



a. Stations B and C are not in each other's range.



b. Stations B and C are hidden from each other.

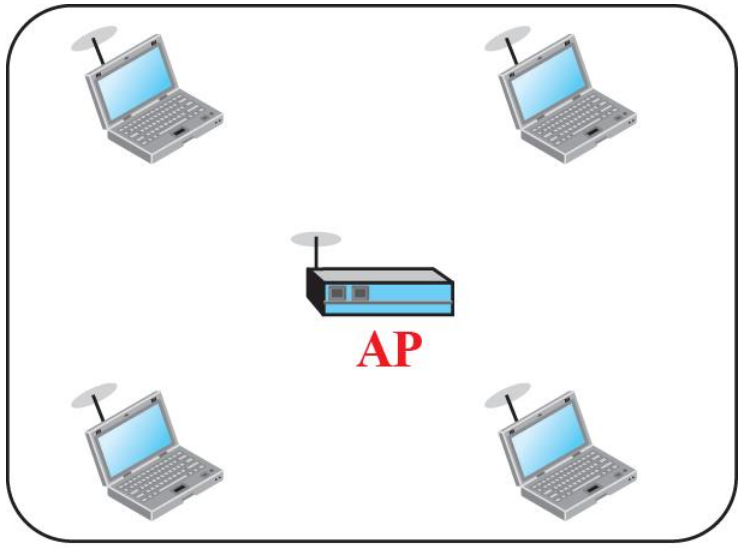
15-2 IEEE 802.11 PROJECT

IEEE has defined the specifications for a wireless LAN, called IEEE 802.11, which covers the physical and data-link layers. It is sometimes called wireless Ethernet. In some countries, including the United States, the public uses the term WiFi (short for wireless fidelity) as a synonym for wireless LAN. WiFi, however, is a wireless LAN that is certified by the WiFi Alliance.

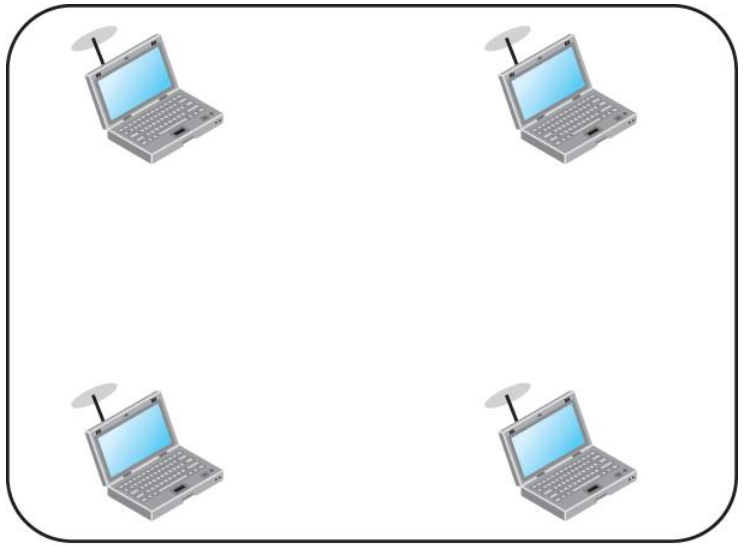
15.2.1 Architecture

The standard defines two kinds of services: the basic service set (BSS) and the extended service set (ESS).

Figure 15.4: Basic service sets (BSSs)

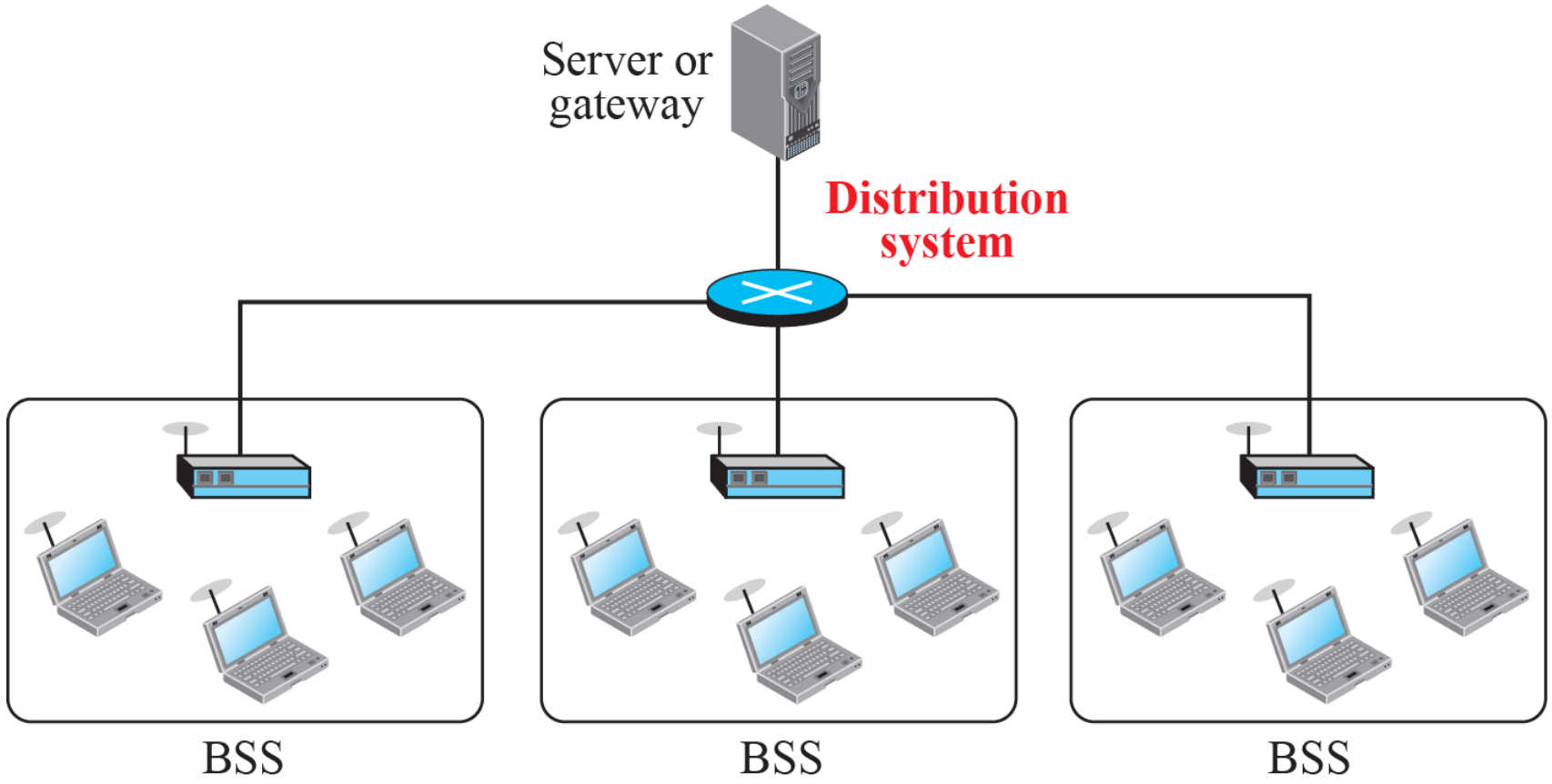


Infrastructure BSS



Ad hoc BSS

Figure 15.6: Extended service set (ESS)



15.2.2 MAC Sublayer

IEEE 802.11 defines two MAC sublayers: the distributed coordination function (DCF) and point coordination function (PCF). Figure 15.6 shows the relationship between the two MAC sublayers, the LLC sublayer, and the physical layer. We discuss the physical layer implementations later in the chapter and will now concentrate on the MAC sublayer.

Figure 15.6: MAC layers in IEEE 802.11 standard

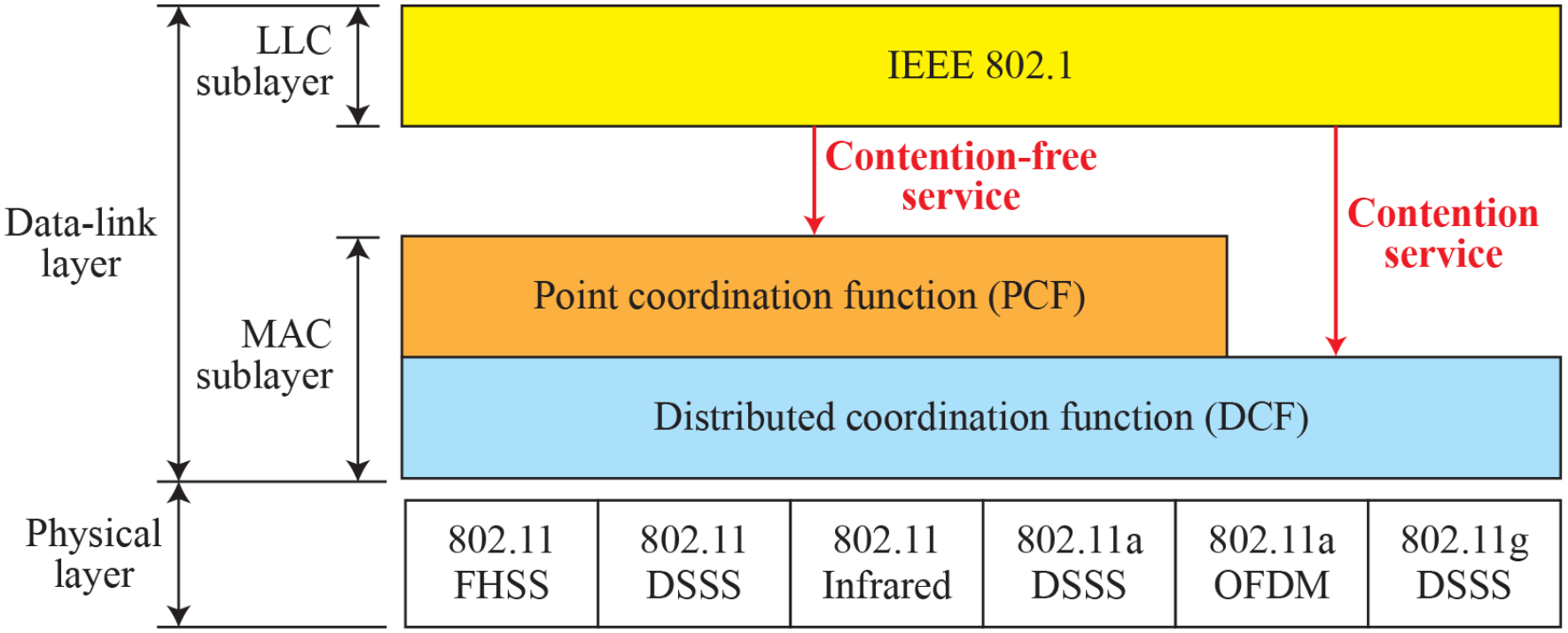


Figure 15.7: CSMA/CA and NAV

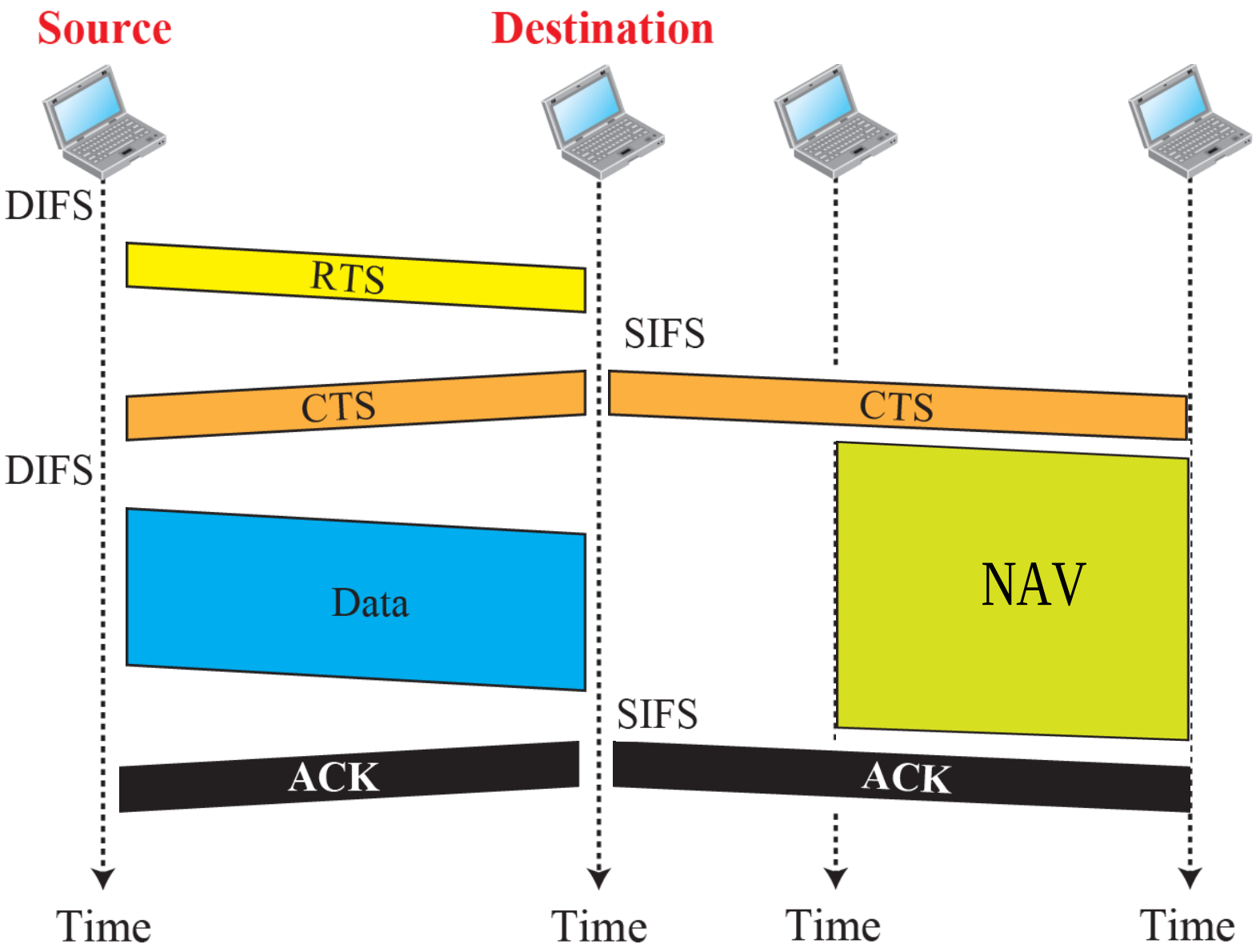


Figure 15.8: Example of repetition interval

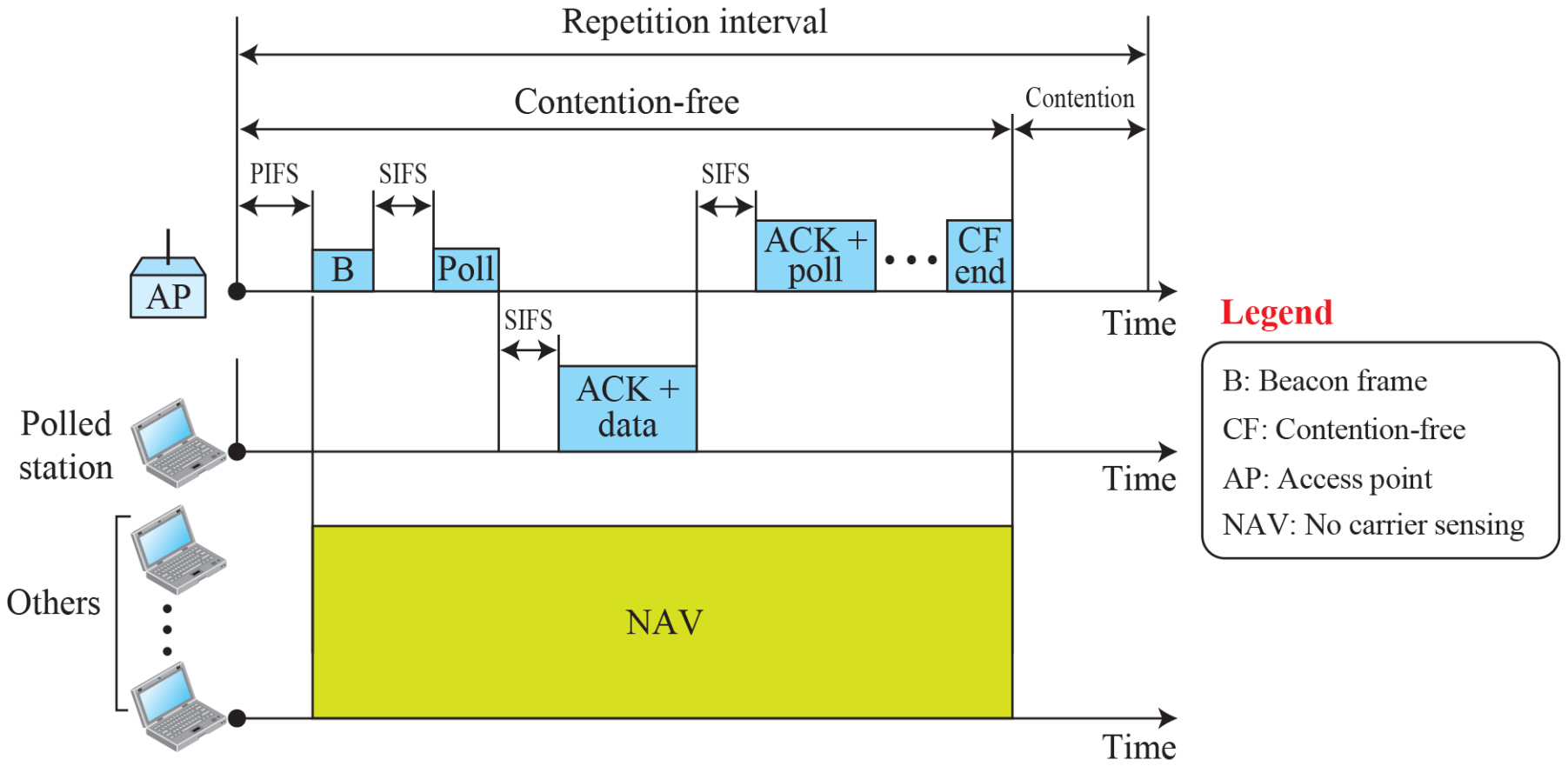
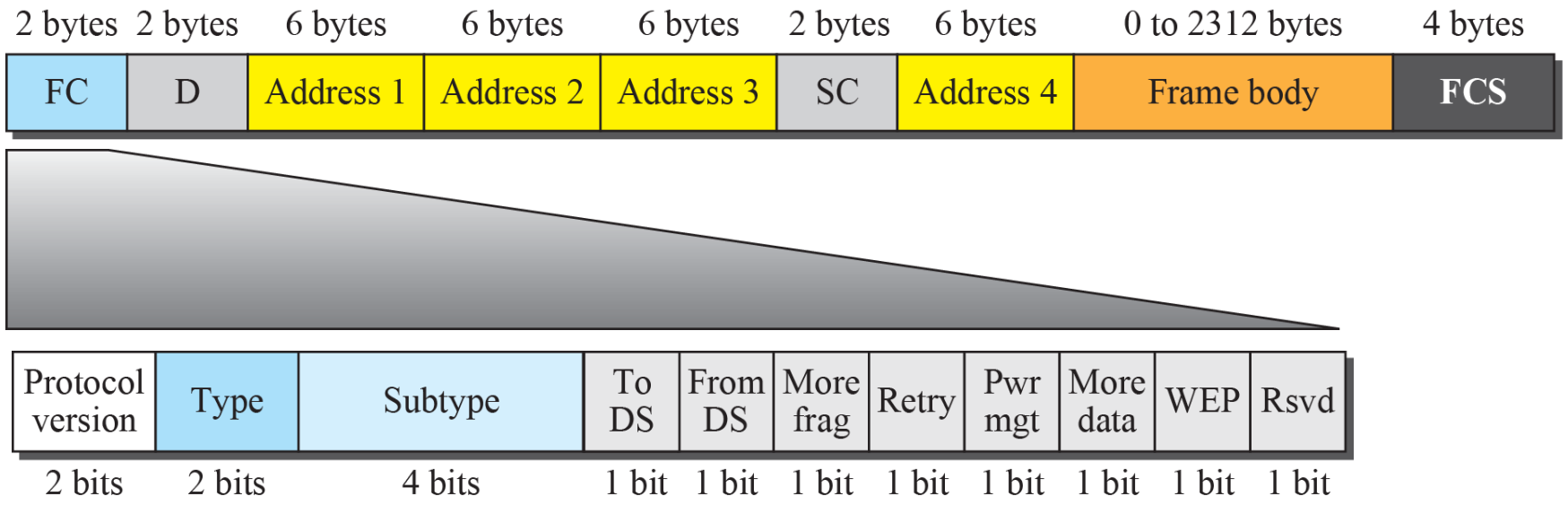


Figure 15.9: Frame format



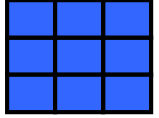
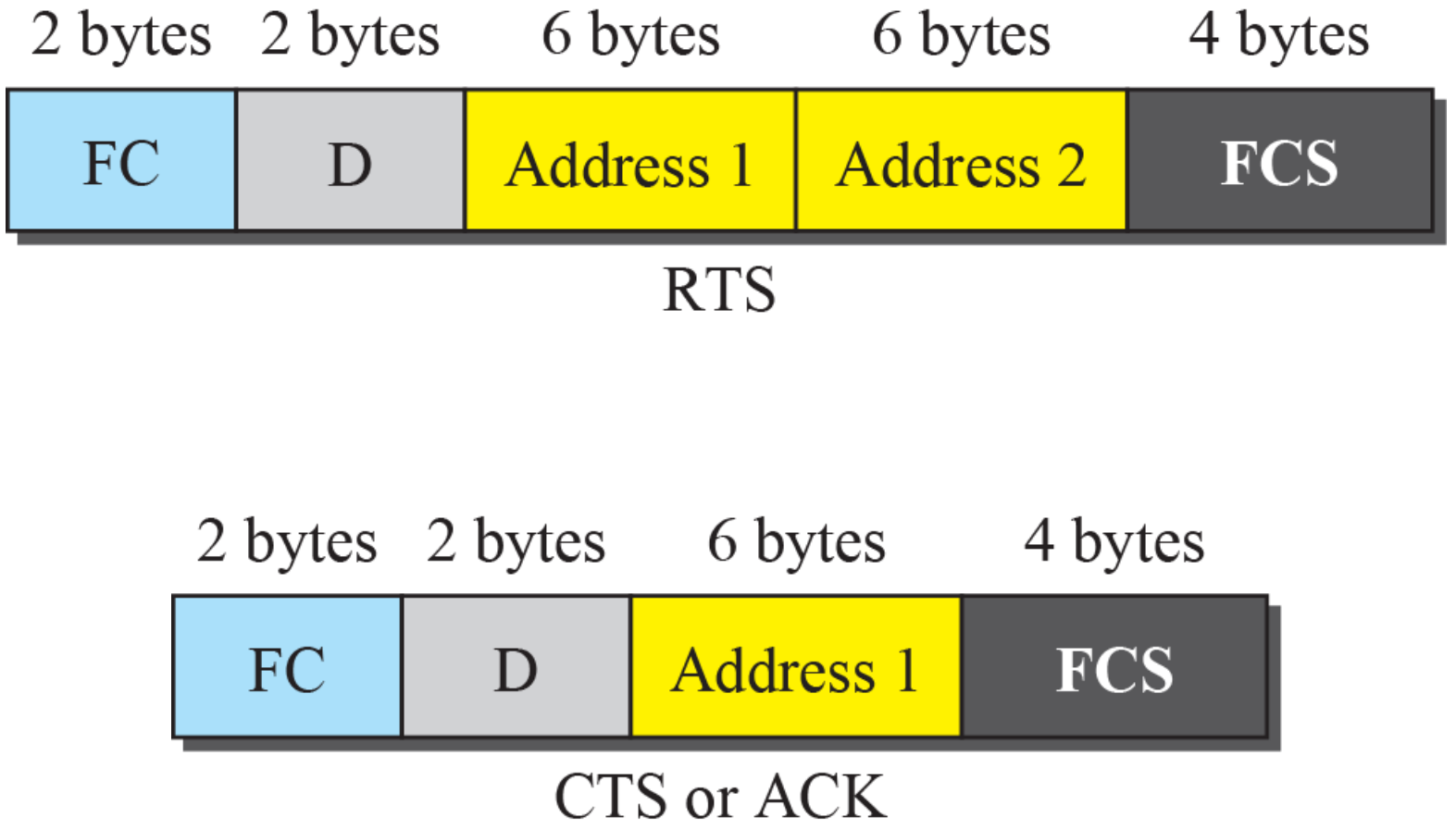


Table 15.1: Subfields in FC field

Field	*Explanation*
Version	Current version is 0
Type	Type of information: management (00), control (01), or data (10)
Subtype	Subtype of each type (see Table 6.2)
To DS	Defined later
From DS	Defined later
More flag	When set to 1, means more fragments
Retry	When set to 1, means retransmitted frame
Pwr mgt	When set to 1, means station is in power management mode
More data	When set to 1, means station has more data to send
WEP	Wired equivalent privacy (encryption implemented)
Rsvd	Reserved

Figure 15.10: Control frames



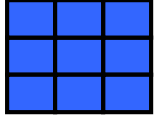


Table 15.2: Values of subfields in control frames

Subtype	*Meaning*
1011	Request to send (RTS)
1100	Clear to send (CTS)
1101	Acknowledgment (ACK)

15.2.3 Addressing Mechanism

The IEEE 802.11 addressing mechanism specifies four cases, defined by the value of the two flags in the FC field, To DS and From DS. Each flag can be either 0 or 1, resulting in four different situations. The interpretation of the four addresses (address 1 to address 4) in the MAC frame depends on the value of these flags, as shown in Table 15.3.

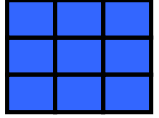
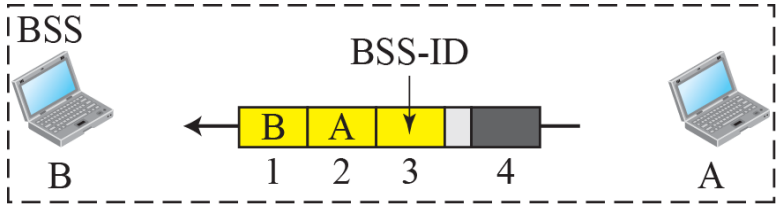


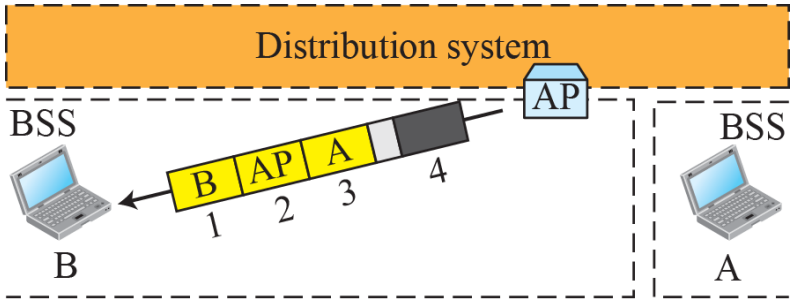
Table 15.3: Addresses

To DS	*From DS*	*Address 1*	*Address 2*	*Address 3*	*Address 4*
0	0	Destination	Source	BSS ID	N/A
0	1	Destination	Sending AP	Source	N/A
1	0	Receiving AP	Source	Destination	N/A
1	1	Receiving AP	Sending AP	Destination	Source

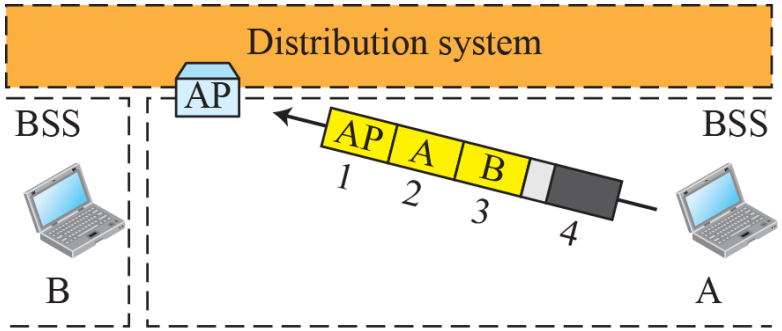
Figure 15.11: Addressing mechanisms



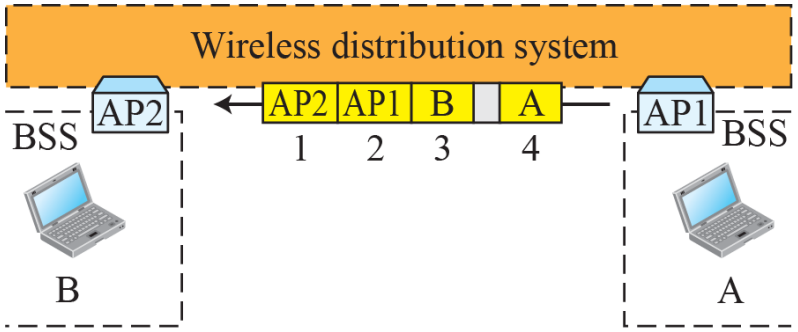
a. Case 1



b. Case 2

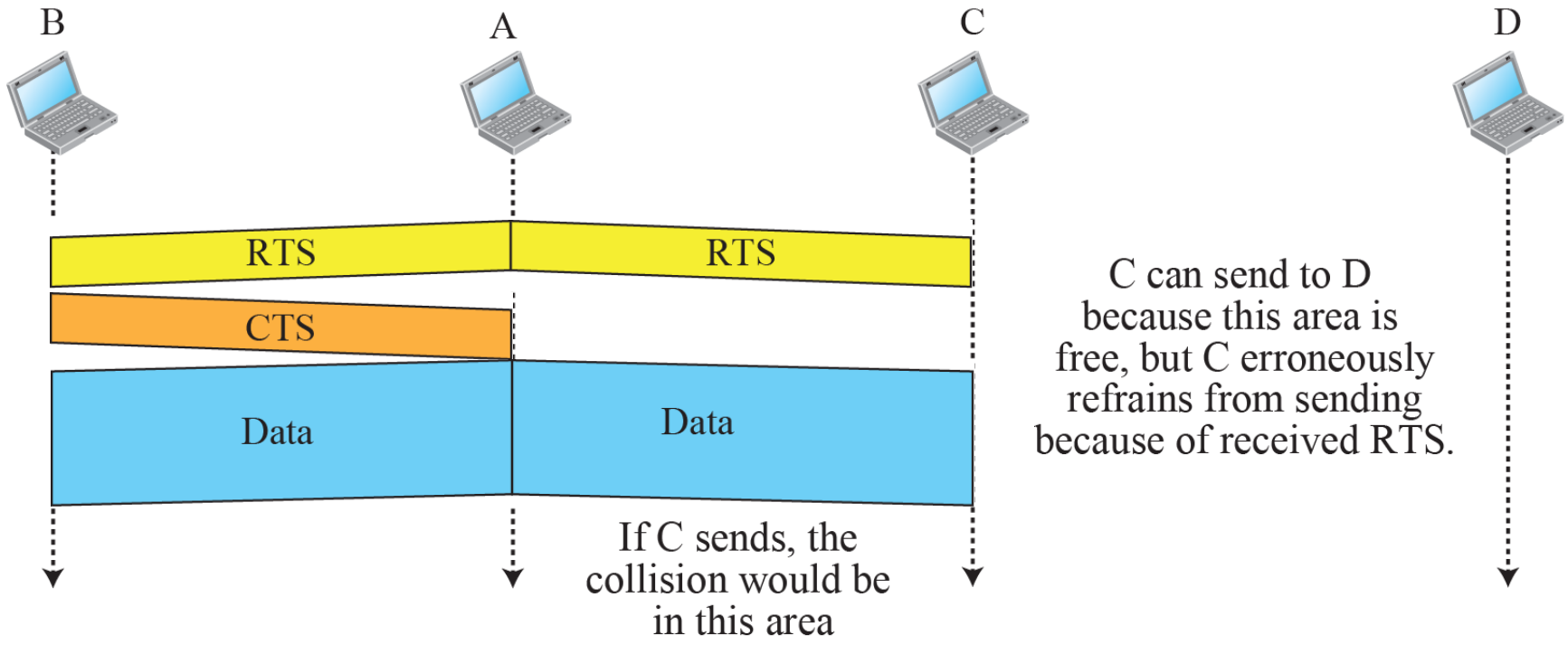


c. Case 3



d. Case 4

Figure 15.12: Exposed station problem



15.2.4 Physical Layer

We discuss six specifications, as shown in Table 15.4. All implementations, except the infrared, operate in the industrial, scientific, and medical (ISM) band, which defines three unlicensed bands in the three ranges 902–928 MHz, 2.400–4.835 GHz, and 5.725–5.850 GHz.

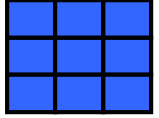


Table 15.4: Specifications

IEEE	*Technique*	*Band*	*Modulation*	*Rate (Mbps)*
802.11	FHSS	2.400–4.835 GHz	FSK	1 and 2
	DSSS	2.400–4.835 GHz	PSK	1 and 2
	None	Infrared	PPM	1 and 2
802.11a	OFDM	5.725–5.850 GHz	PSK or QAM	6 to 54
802.11b	DSSS	2.400–4.835 GHz	PSK	5.5 and 11
802.11g	OFDM	2.400–4.835 GHz	Different	22 and 54
802.11n	OFDM	5.725–5.850 GHz	Different	600

Figure 15.13: Physical layer of IEEE 802.11 FHSS

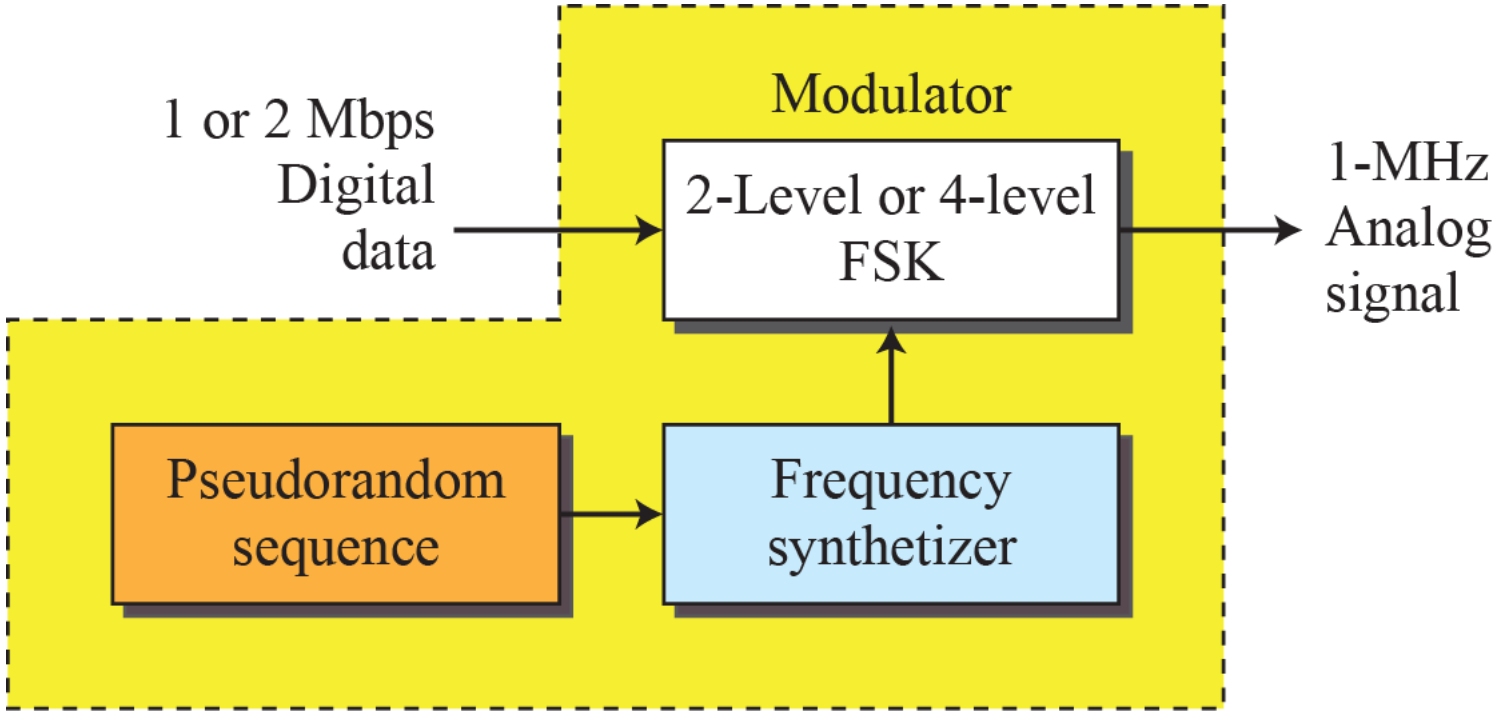


Figure 15.14: Physical layer of IEEE 802.11 DSSS

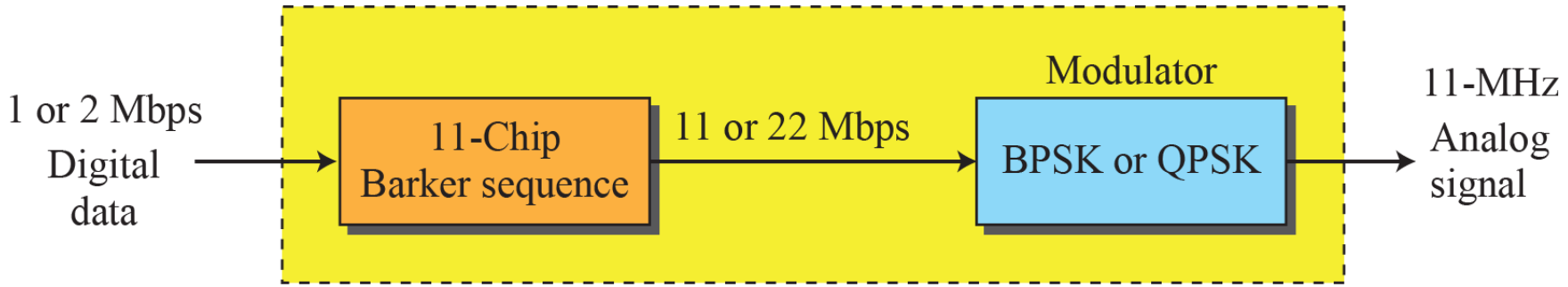


Figure 15.15: Physical layer of IEEE 802.11 infrared

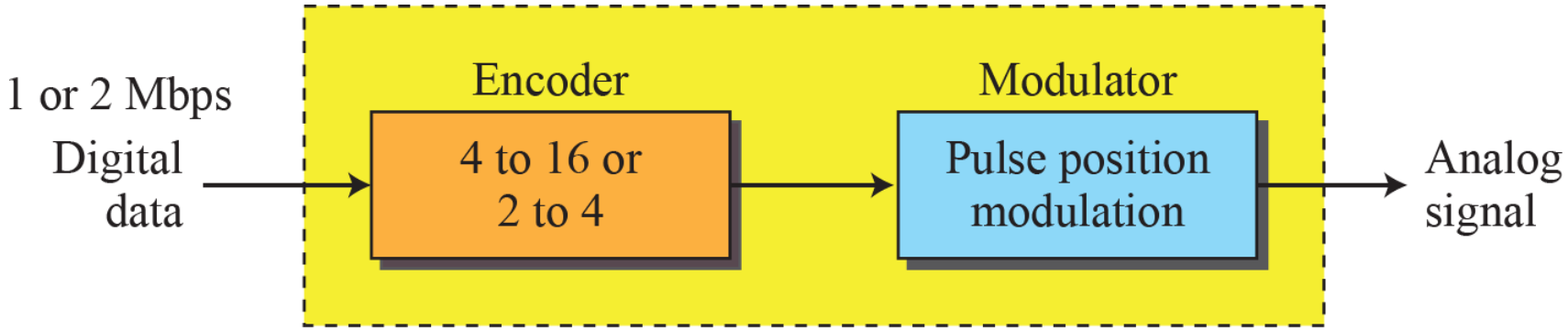
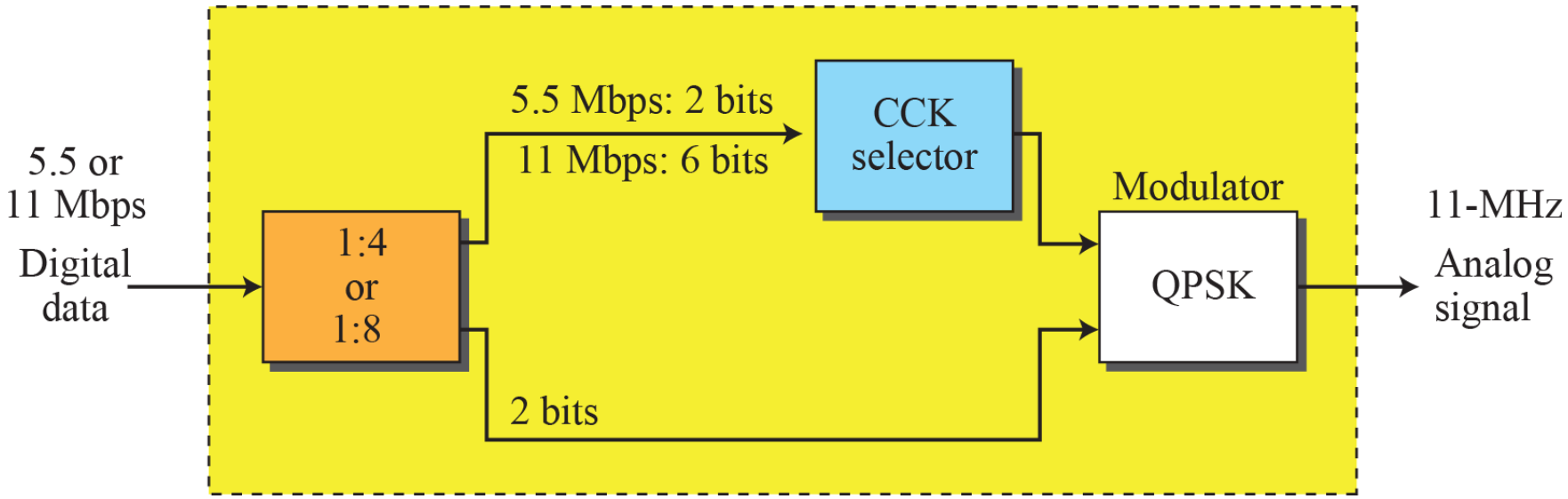


Figure 15.16: Physical layer of IEEE 802.11b



15-3 BLUETOOTH

Bluetooth is a wireless LAN technology designed to connect devices of different functions when they are at a short distance from each other. A Bluetooth LAN is an ad hoc network. The devices, sometimes called gadgets, find each other and make a network called a piconet.

15.3.1 Architecture

Bluetooth defines two types of networks: piconet and scatternet.

Figure 6.17: Piconet

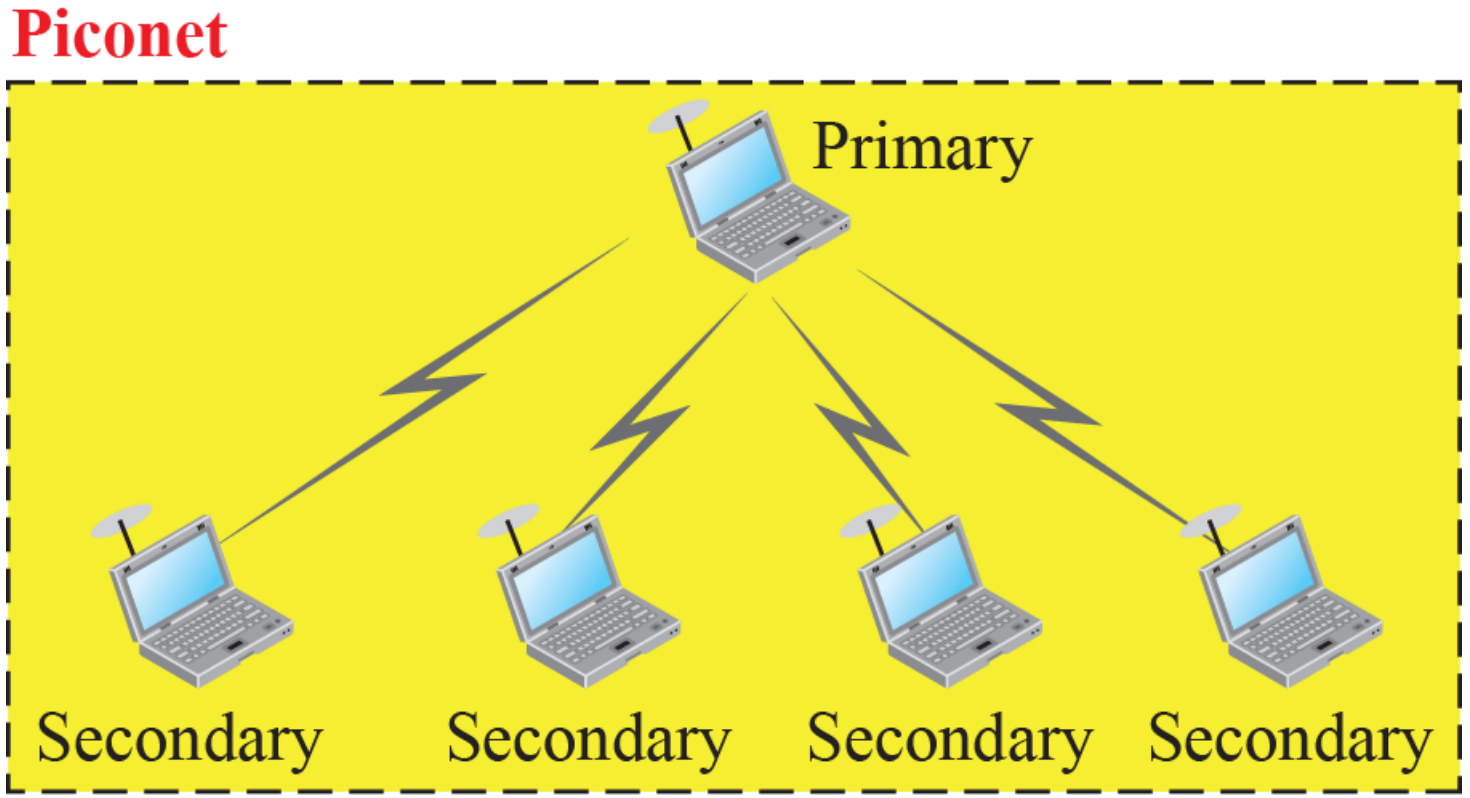
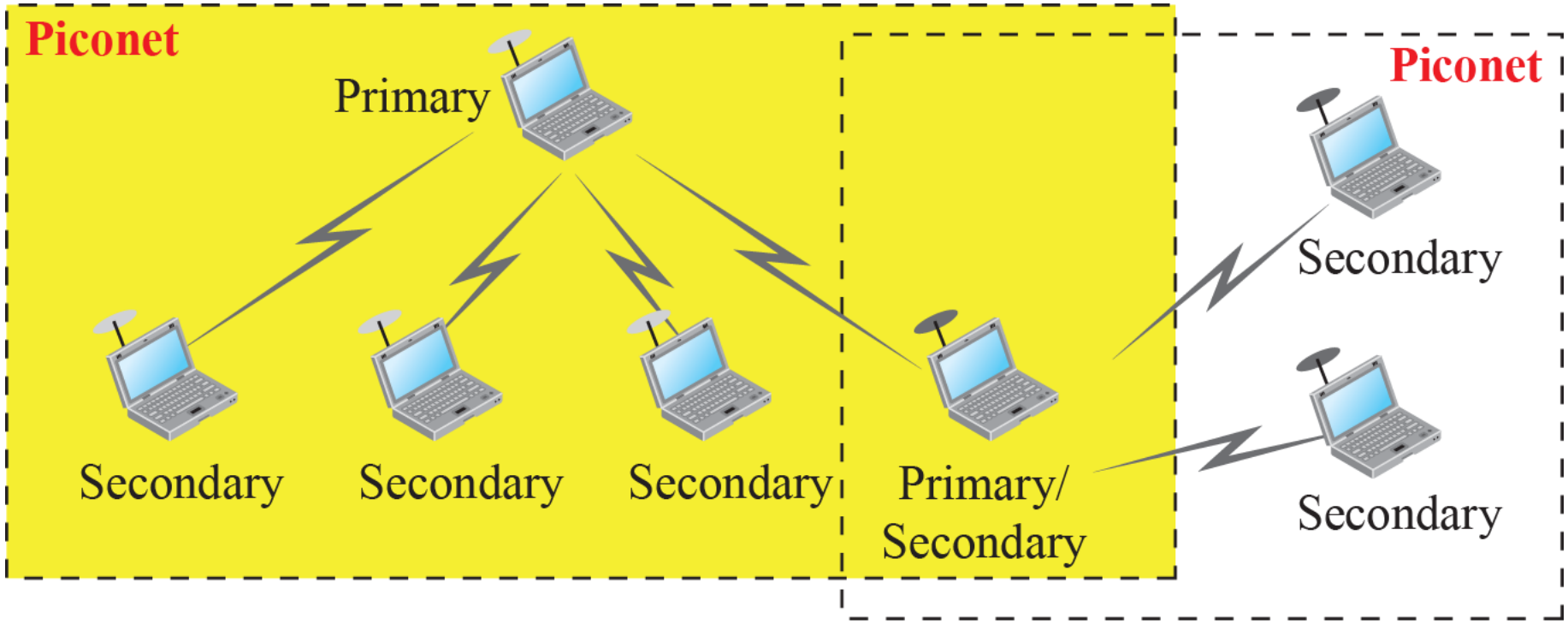


Figure 15.18: Scatternet



15.3.2 Bluetooth Layers

Bluetooth uses several layers that do not exactly match those of the Internet model we have defined in this book. Figure 15.19 shows these layers.

Figure 15.19: Bluetooth layers

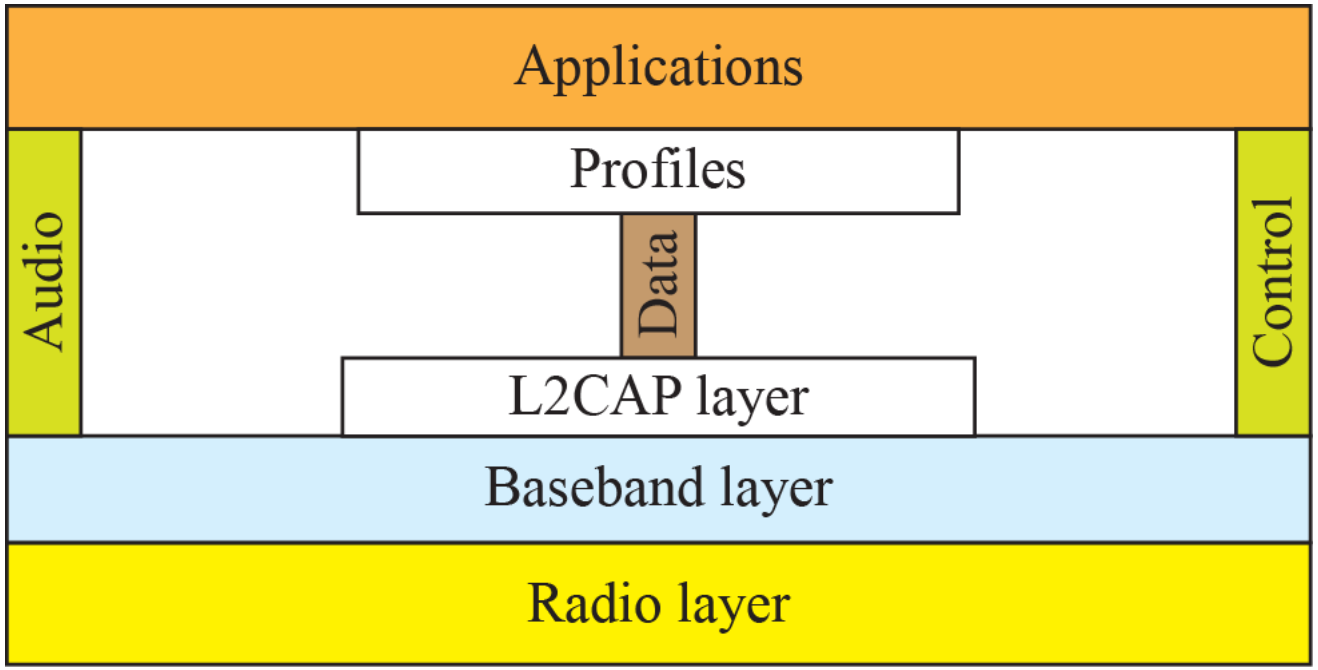


Figure 15.20: L2CAP data packet format



Figure 6.21: Single-secondary communication

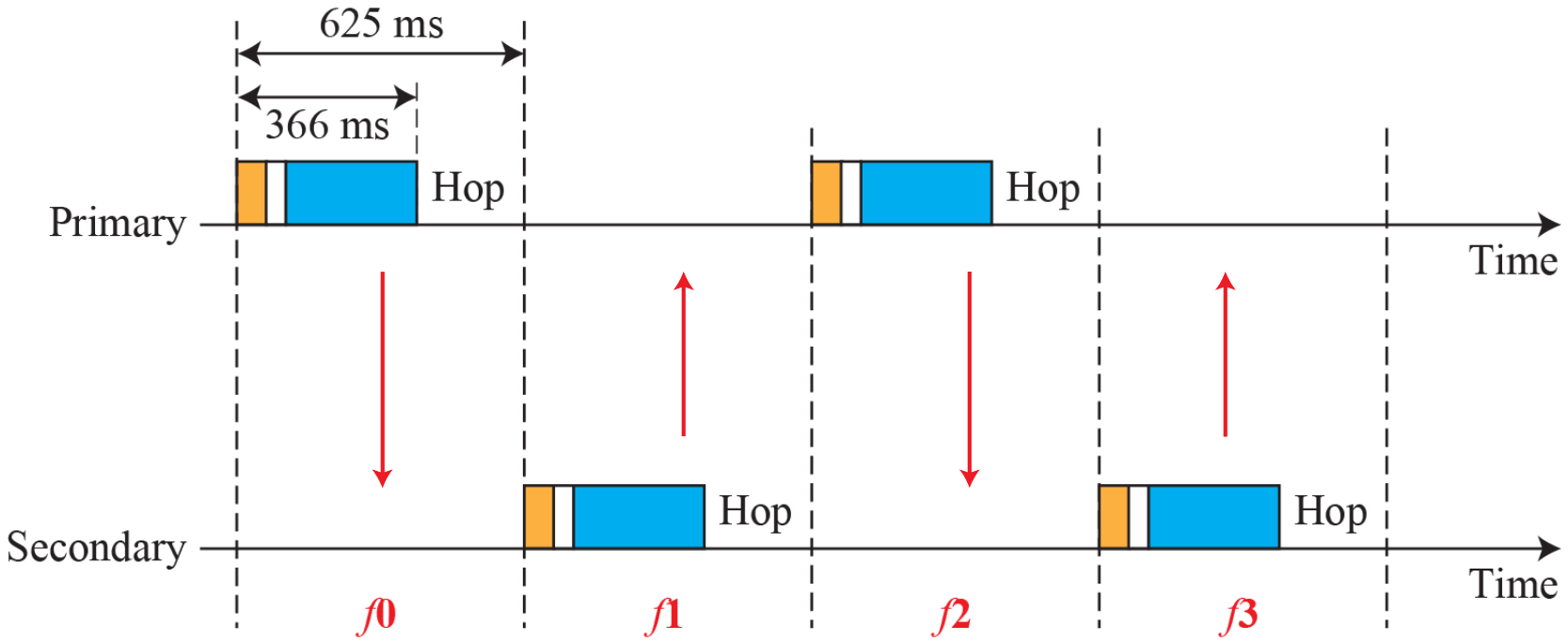


Figure 6.22: Multiple-secondary communication

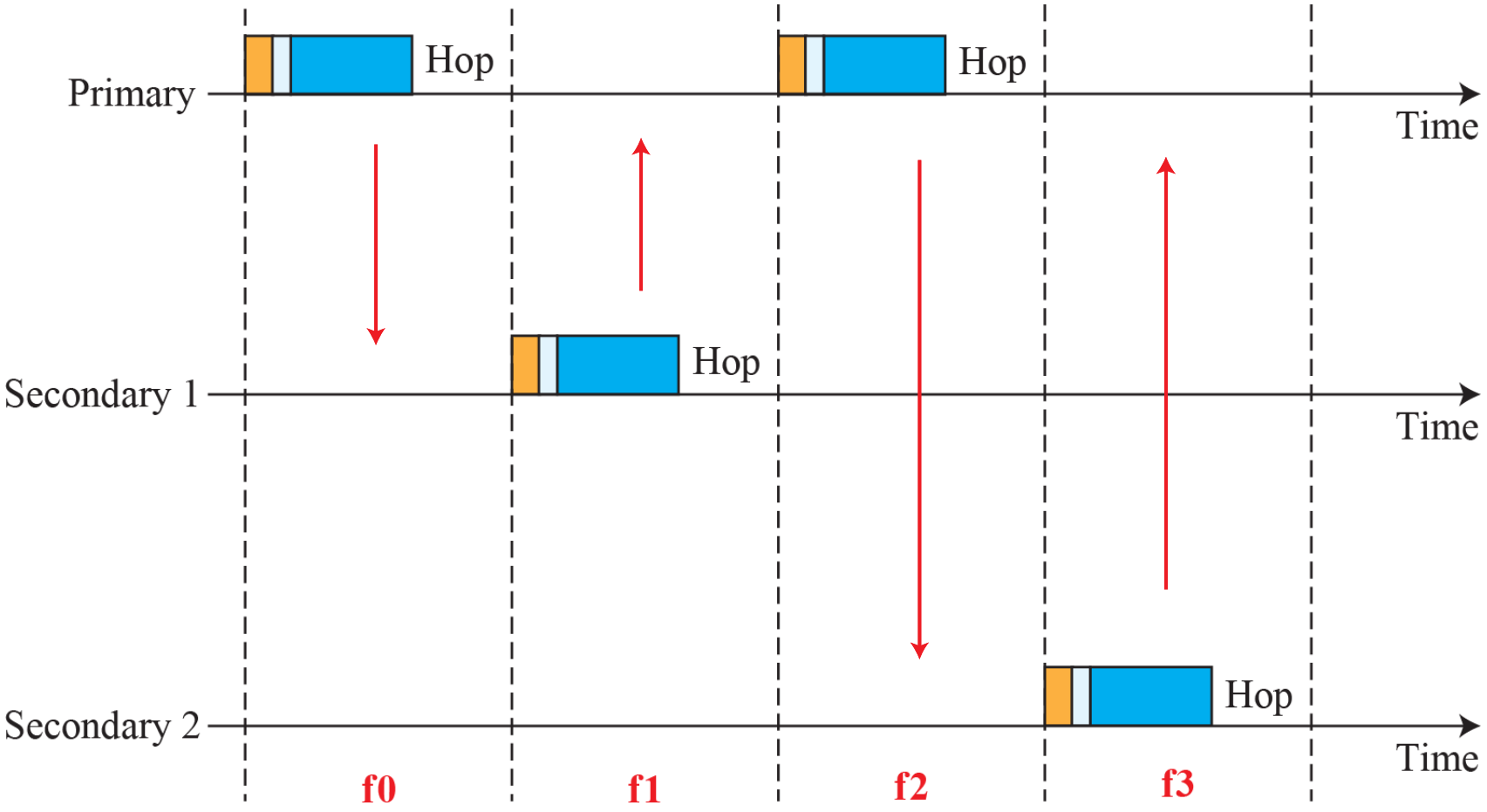
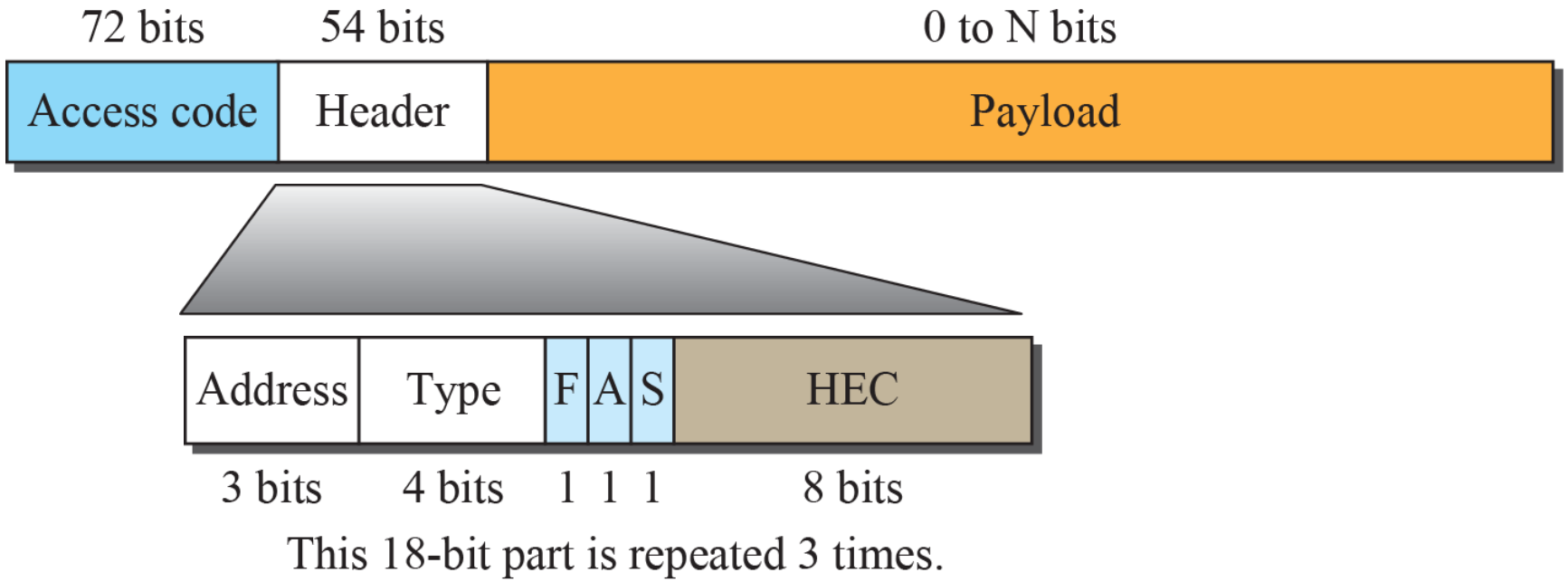


Figure 6.23: Frame format types



N = 240 for 1-slot frame

N = 1490 for 3-slot frame

N = 2740 for 5-slot frame

Ch. 16 (supplement)

Mobile Communication Networks

Generations

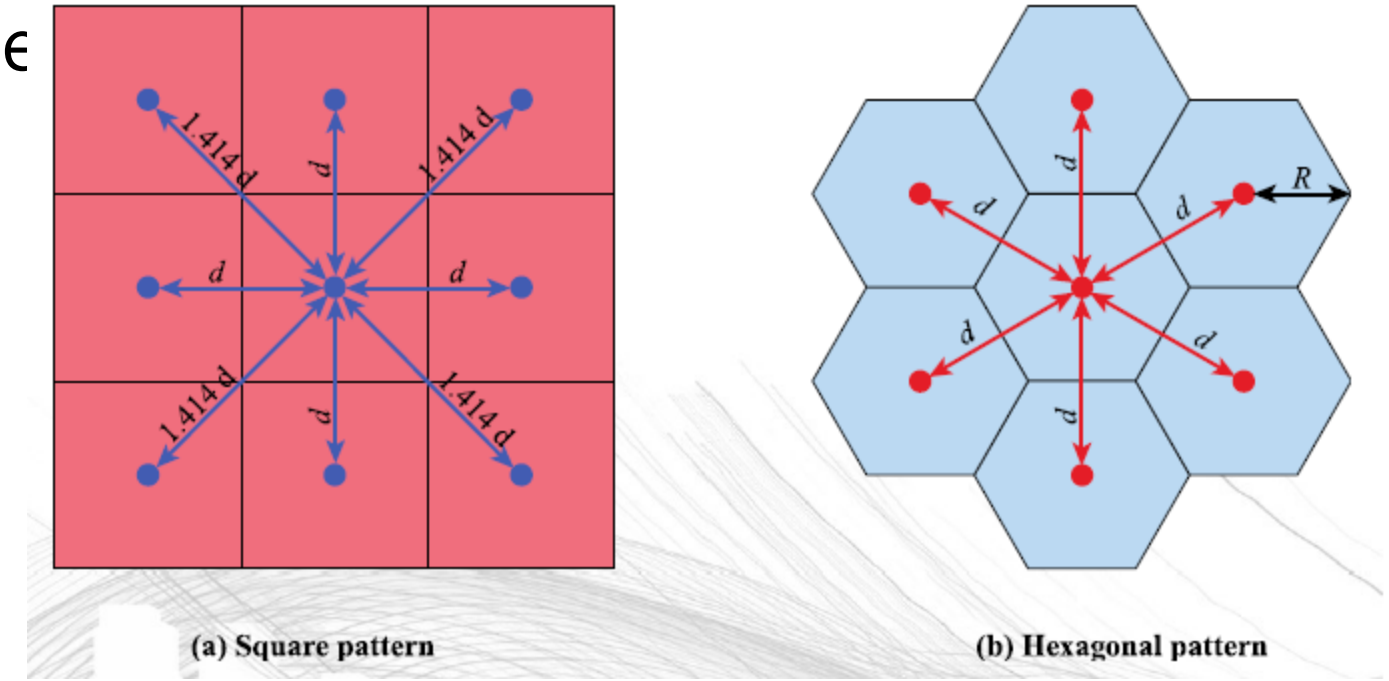
- Each generation is 10 years
  - 1G (1980s): analog, voice
  - 2G (1990s): digital, voice
  - 3G (2000s): packets, data replaces voices
  - 4G (2010s): IP, broadband
  - 5G (2020s): softwarization
  - 6G (2030s): ?

Cellular network organization

- Use multiple low-power transmitters (100 W or less)
- Areas divided into cells
  - Each served by its own antenna
  - Served by base station consisting of transmitter, receiver, and control unit
  - Band of frequencies allocated
  - Cells set up such that antennas of all neighbors are equidistant (hexagonal pattern)
    - Idealized pattern, in order to approximate coverage
    - In reality, less regular

Cellular network organization

- Cellular ge



Cellular network organization

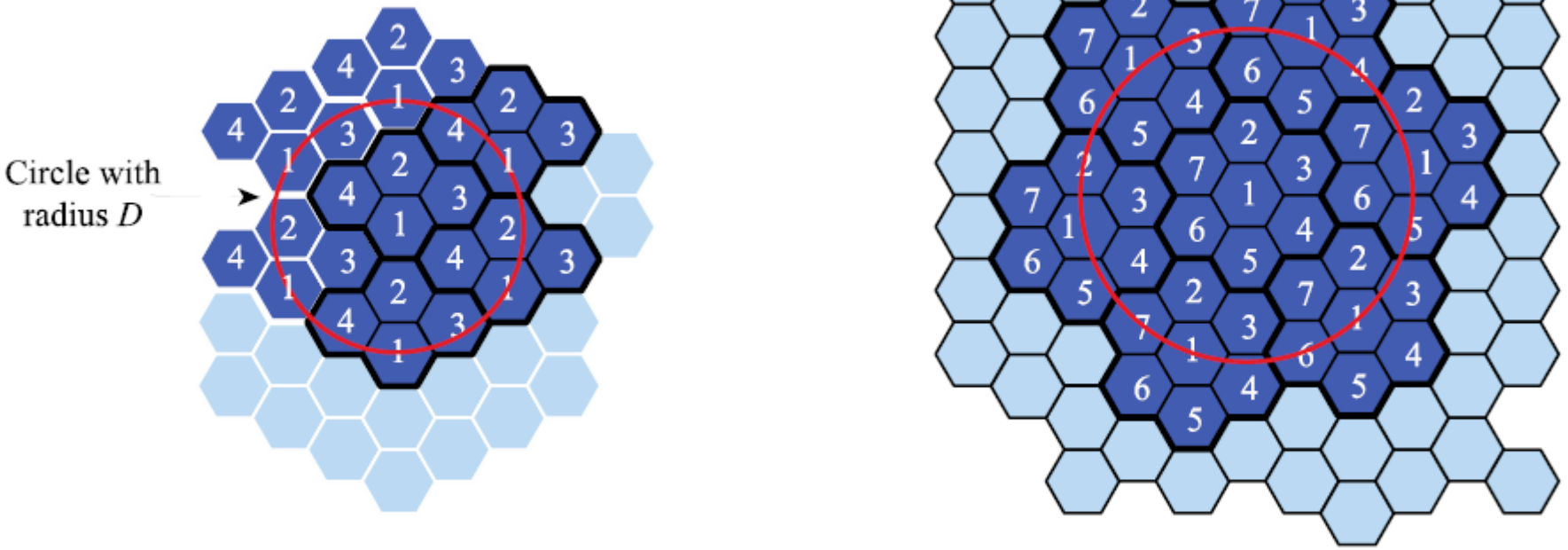
- Why not a large service area
  - Number of simultaneous user to serve would be limited
  - Mobile handset needs to have larger power requirement
- Smaller cells
  - Allows frequency reuse, hence increased capacity for the same area of coverage
  - Lower power handset
  - Cons : Cost of cells, hands off between cells must be supported, need to track user to route incoming call or message

Frequency reuse

- Adjacent cells assigned different frequencies to avoid interference or crosstalk
- Objective is to reuse frequency in nearby cells
  - 10 to 50 frequencies assigned to each cell
  - Transmission power controlled to limit power at that frequency escaping to adjacent cells
  - The issue is to determine how many cells must intervene between two cells using the same frequency

Frequency reuse

- Frequency reuse factor
  - Move I cells along any chain of hexagons, and turn 60 degrees ccw and move J steps: $N = I^2 + J^2 + IJ$

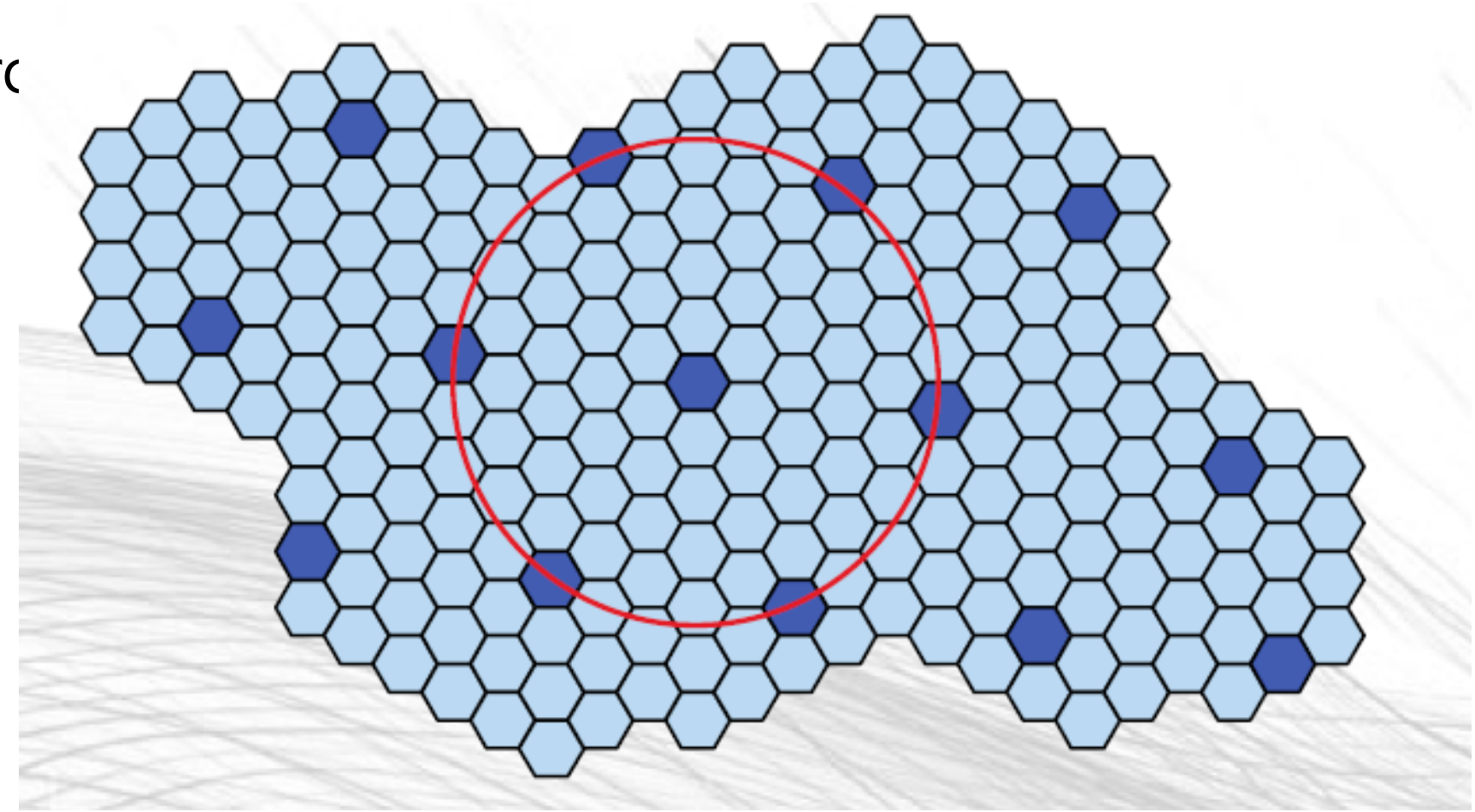


(a) Frequency reuse pattern for $N = 4$

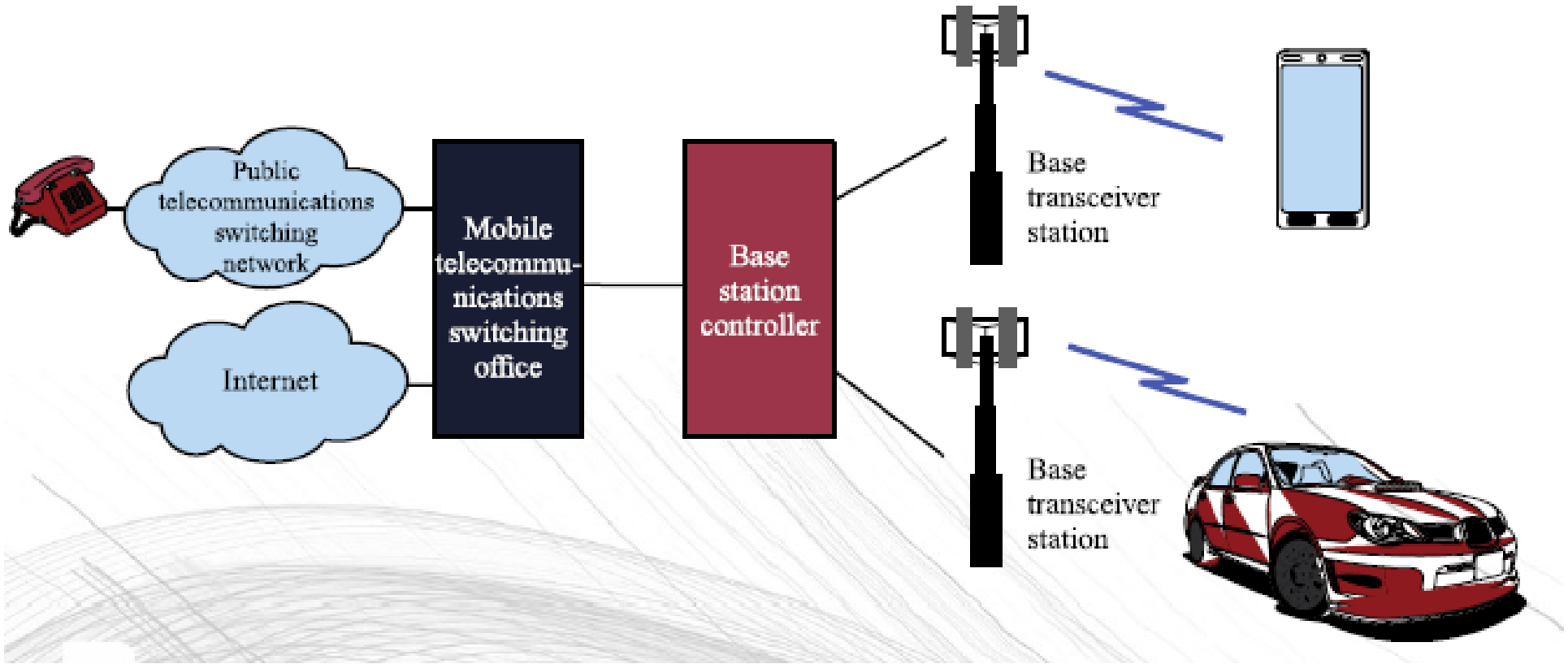
(b) Frequency reuse pattern for $N = 7$

Frequency reuse

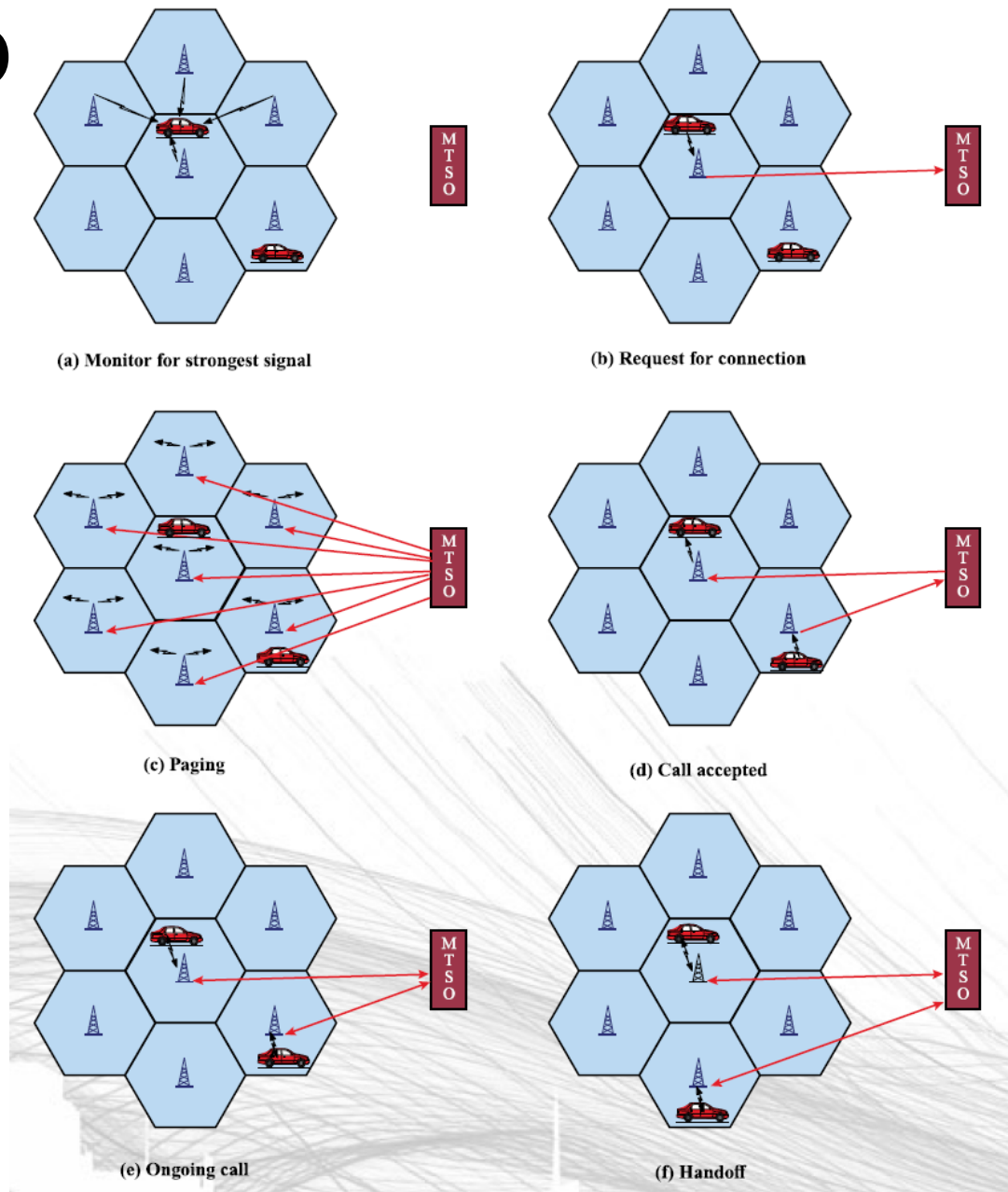
- Exerc



Cellular system overview



Example o


MTSO
(a) Monitor for strongest signal
MTSO
(b) Request for connection
MTSO
(c) Paging
MTSO
(d) Call accepted
MTSO
(e) Ongoing call
MTSO
(f) Handoff

Free space loss

- P_t = signal power at transmitting antenna
- P_r = signal power at receiving antenna
- λ = carrier wavelength
- d = propagation distance between antennas
- c = speed of light (3×10^8 m/s)

$$\frac{P_r}{P_t} = \frac{\lambda^2}{(4\pi d)^2} = \frac{c^2}{(4\pi f d)^2}$$

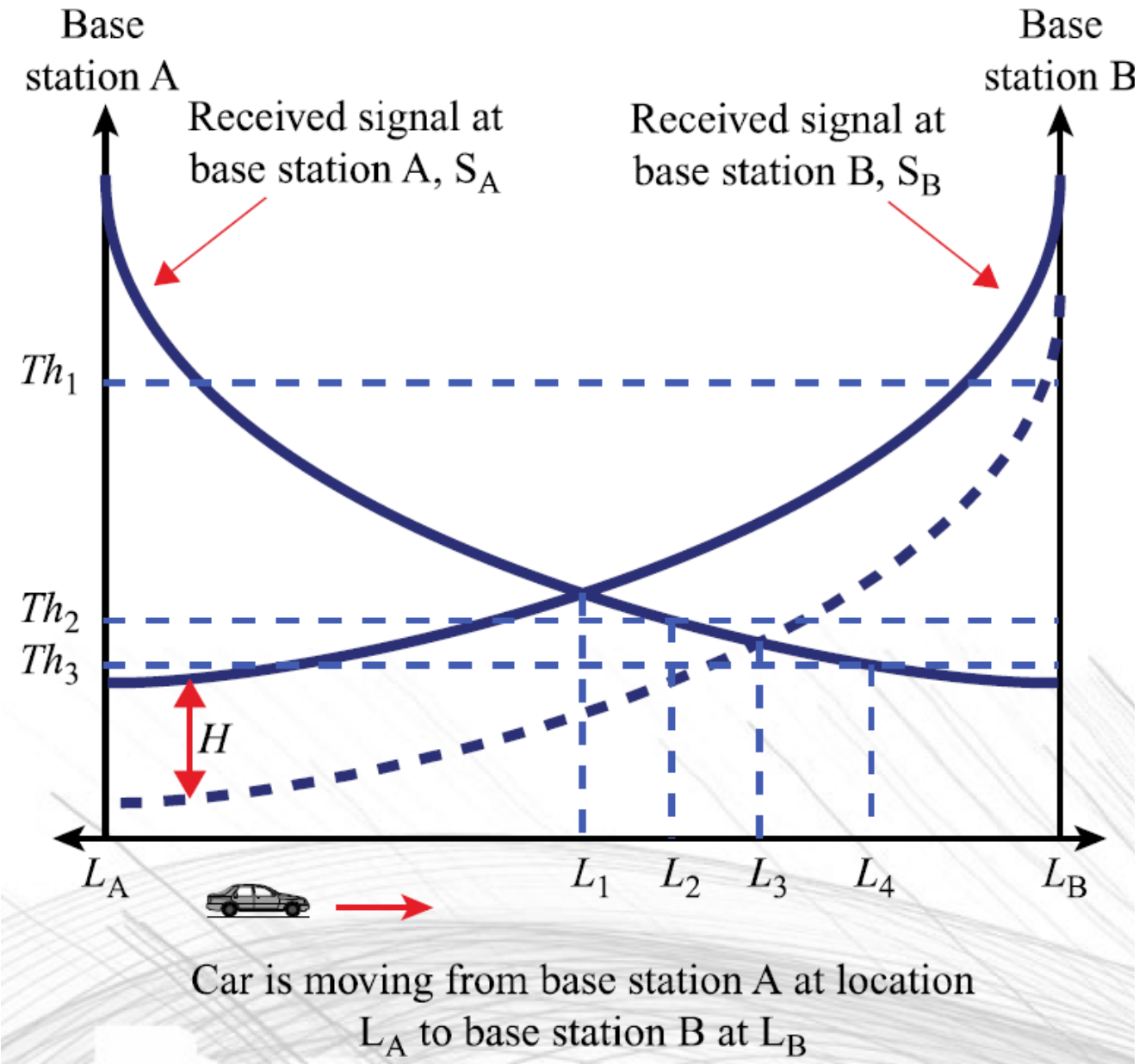
Free space loss

- In practice, received power decreases logarithmically with distance

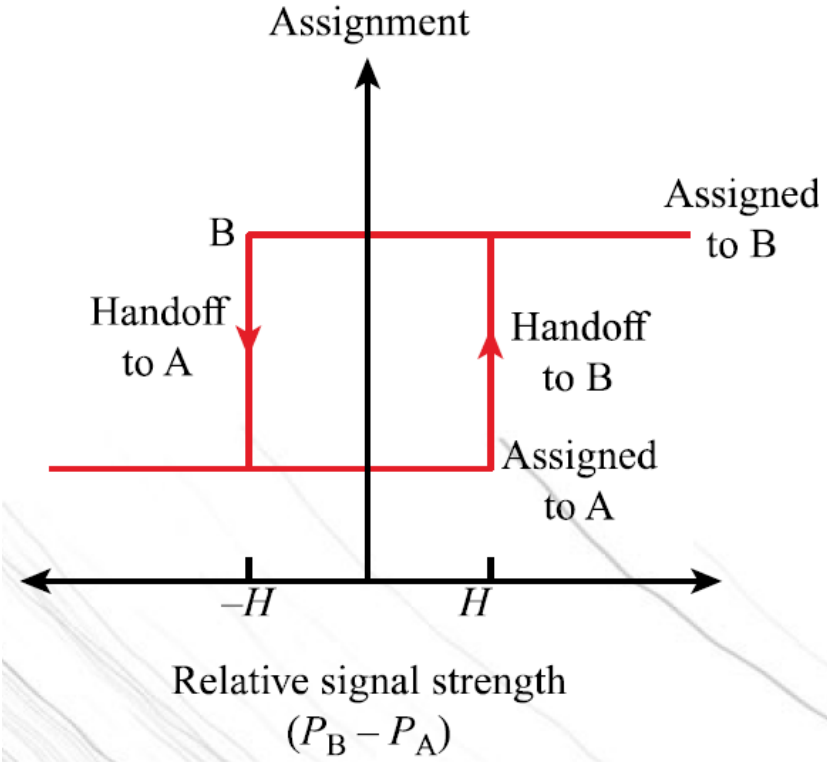
$$\frac{P_r}{P_t} = \frac{\lambda^2}{(4\pi d)^2} = \frac{c^2}{(4\pi f)^2 d^n} \Rightarrow L = 20\log(f) + 10n\log(d) - 147.56$$

- Value of n

Environment	Path Loss Exponent, n
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3



Car is moving from base station A at location L_A to base station B at L_B



Handoff strategies

- Relative signal strength $\rightarrow L_1$
  - Prone to trigger too many unnecessary handovers, even when the signal strength of the source BS is still at an acceptable level
- Relative signal strength w/ threshold $\rightarrow T_1: L_1,\ T_2: L_2,\ T_3: L_4$
- Relative signal strength w/ hysteresis $\rightarrow L_3$

Identifiers in GSM

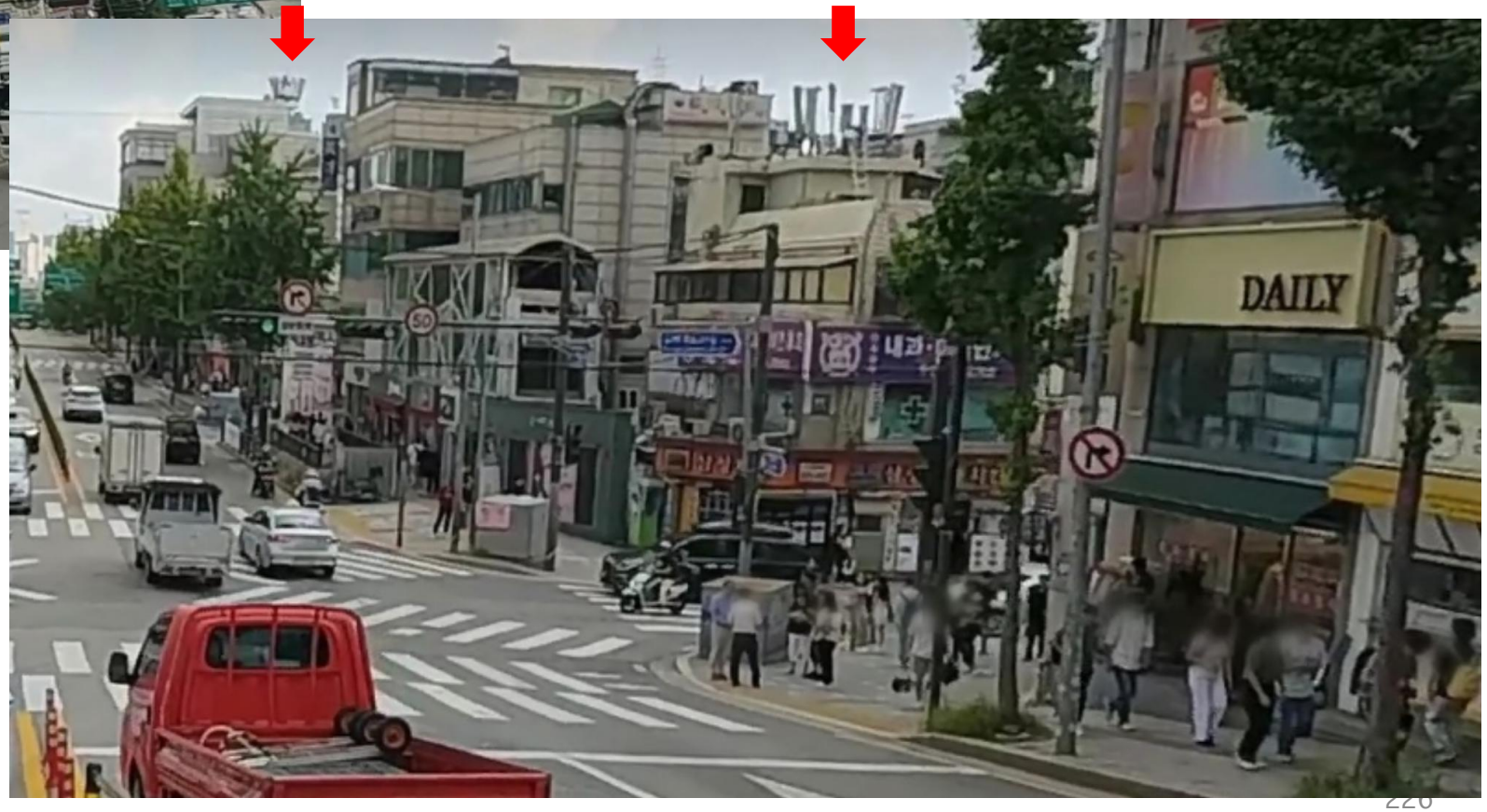
- IMSI (International Mobile Subscriber Identity)
  - Uniquely identifies a GSM subscriber
  - Stored in SIM, does not change over time
- MSISDN (Mobile Station International Subscriber Directory Number)
  - Dialed number
  - Different MSISDN can be associated with a SIM
- IMEI (International Mobile Equipment Identity)
  - Identifies the physical unit mobile equipment

Long Term Evolution (LTE)



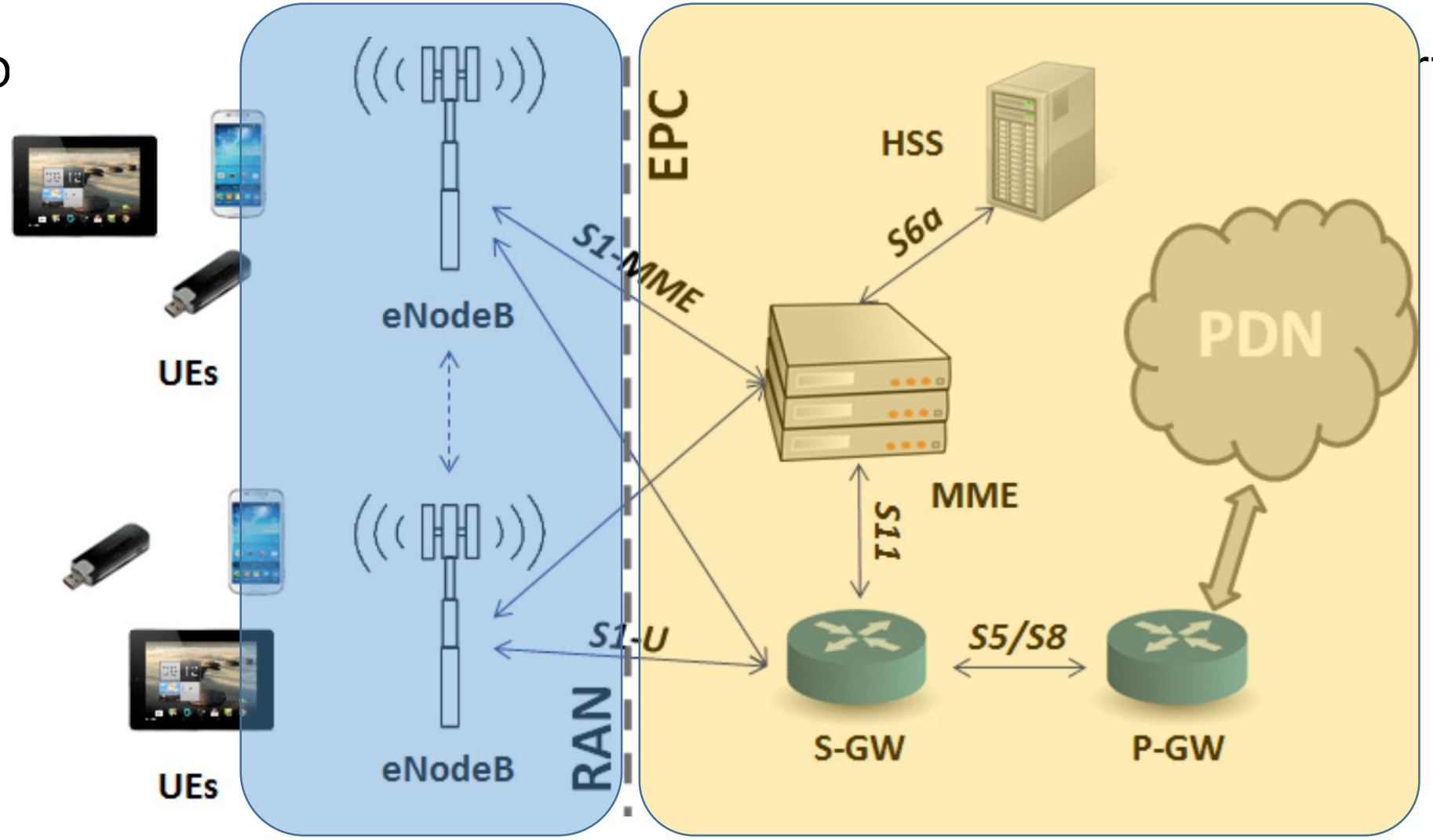
Background: Base stations near Anam





Introduction

- Mo rts



Introduction

- 4th Generation Cellular (Mobile) Communication
  - 2010s
- Came along when Internet traffic was exploding
- Naturally, the goal was providing “broadband”(= high speed)
  - Mostly in download (upload is relatively weak)
    - Up to 100 Mbps in high mobility
    - Up to 1 Gbps in low mobility
- LTE is actually the name of the radio access network (RAN)
  - Core network in 4G is called Evolved Packet Core (EPC)
  - “Evolved” = All IP

Generations

- 4G no longer supports circuit-switched voice
  - Even voice is carried by IP packets over LTE ("Voice over LTE")
- Like IP for core network, OFDM is the biggest success for RAN
  - Both c

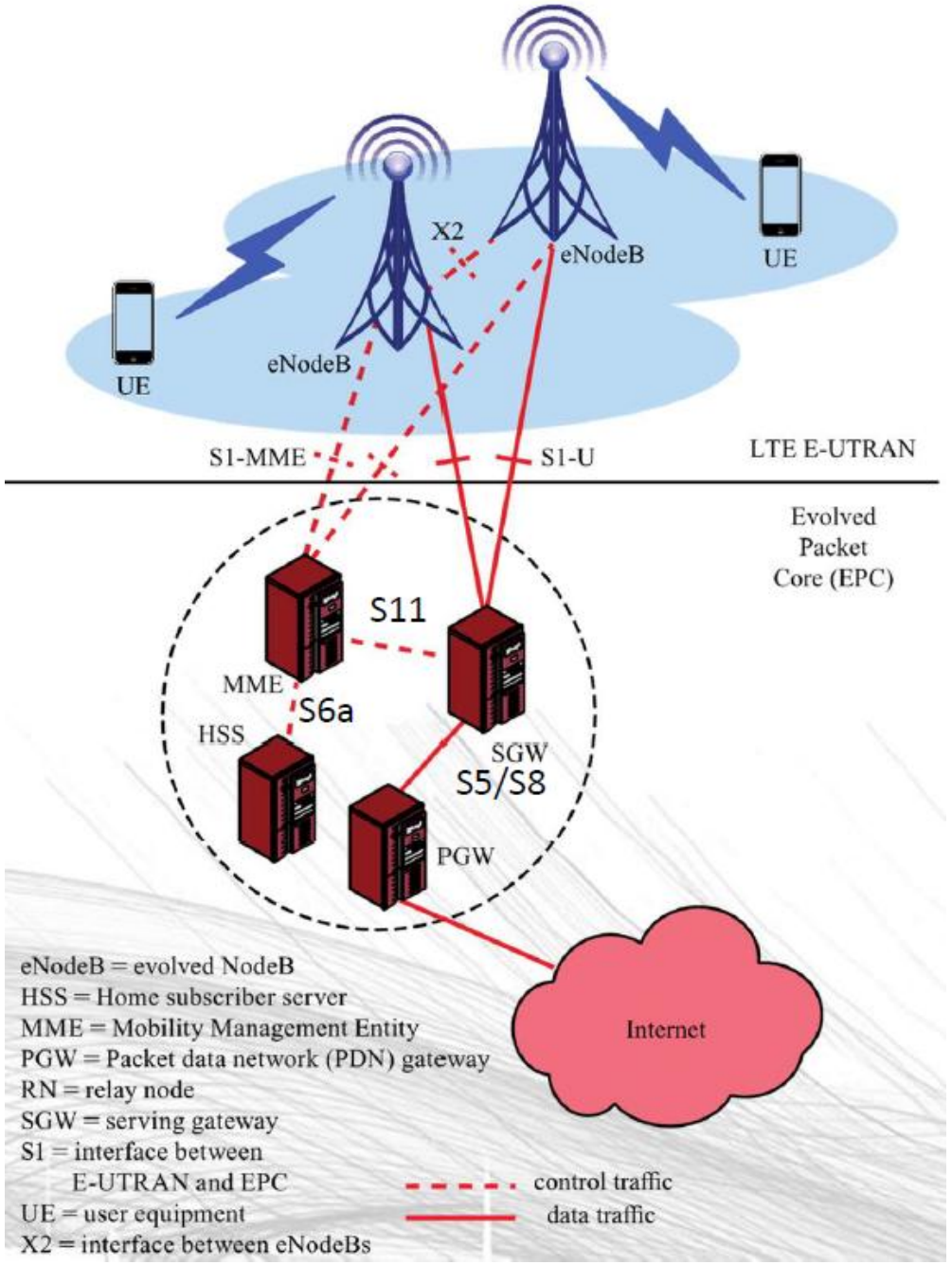
Technology	1G	2G	2.5G	3G	4G
Design began	1970	1980	1985	1990	2000
Implementation	1984	1991	1999	2002	2012
Services	Analog voice	Digital voice	Higher capacity packetized data	Higher capacity, broadband	Completely IP based
Data rate	1.9. kbps	14.4 kbps	384 kbps	2 Mbps	200 Mbps
Multiplexing	FDMA	TDMA, CDMA	TDMA, CDMA	CDMA	OFDMA, SC-FDMA
Core network	PSTN	PSTN	PSTN, packet network	Packet network	IP backbone

LTEs

System Performance		LTE	LTE-Advanced
Peak rate	Downlink	100 Mbps @20 MHz	1 Gbps @100 MHz
	Uplink	50 Mbps @20 MHz	500 Mbps @100 MHz
Control plane delay	Idle to connected	<100 ms	< 50 ms
	Dormant to active	<50 ms	< 10 ms
User plane delay		< 5ms	Lower than LTE
Spectral efficiency (peak)	Downlink	5 bps/Hz @2×2	30 bps/Hz @8×8
	Uplink	2.5 bps/Hz @1×2	15 bps/Hz @4×4
Mobility		Up to 350 km/h	Up to 350—500 km/h

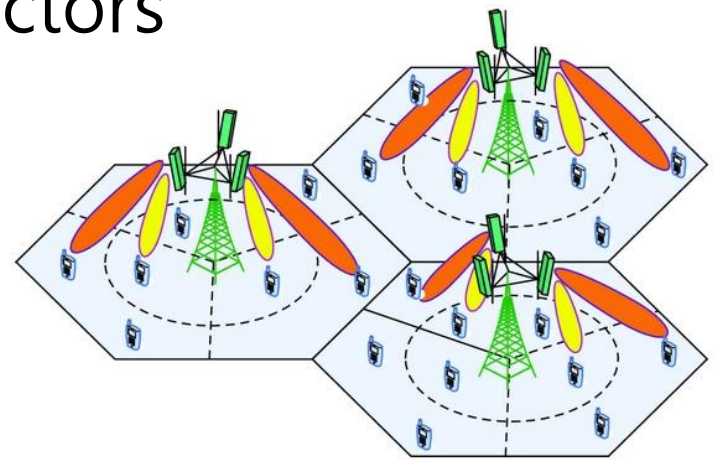
LTE architecture

- Evolved Packet System (EPS)
  - EPS = EPC + LTE
  - EPC and LTE evolve independently
    - LTE = E-UTRAN
  - eNodeB is the base station
    - Logical and more powerful than in 3G
    - Participates in radio resource control, admission control, mobility management
  - Bandwidth
    - 1.4 ~ 20 MHz
    - Up to 100 MHz with carrier aggregation

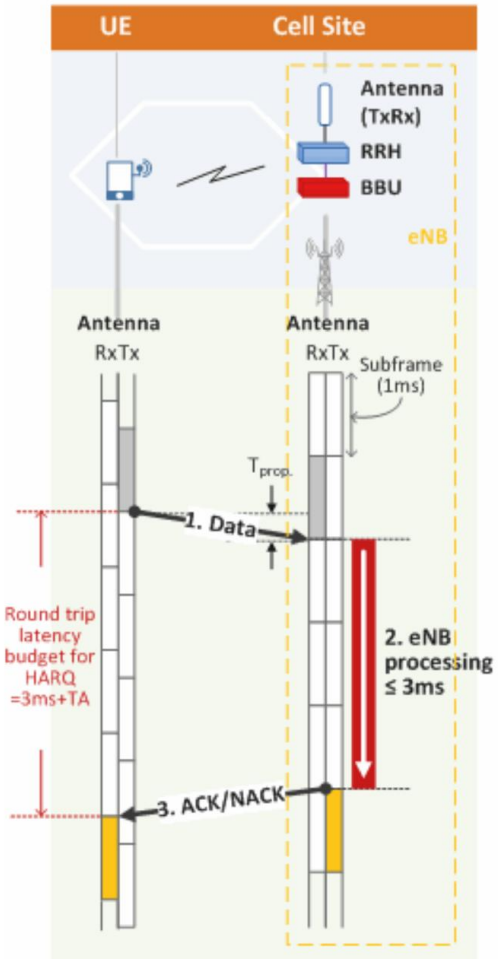


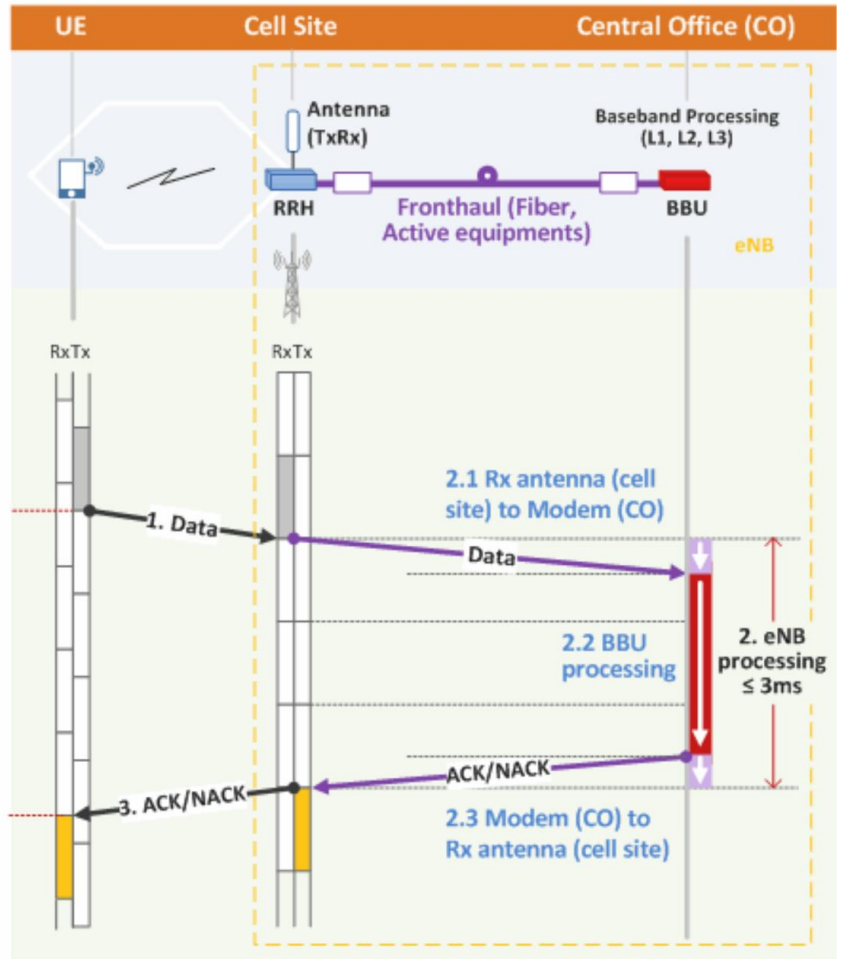
eNodeB is logical

- Can have multiple cells or sectors



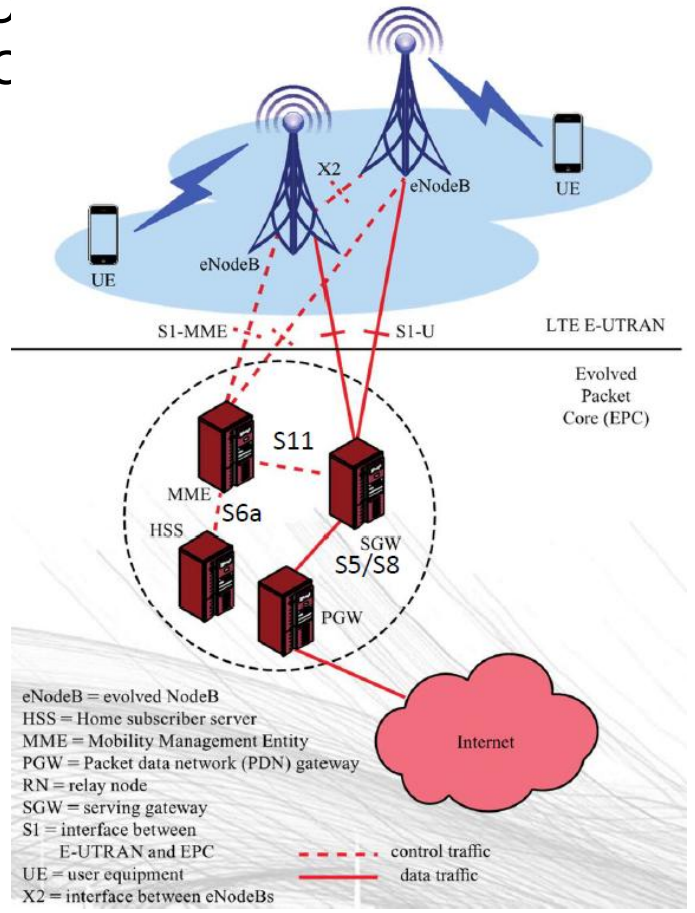
- Some of its processing can be done elsewhere





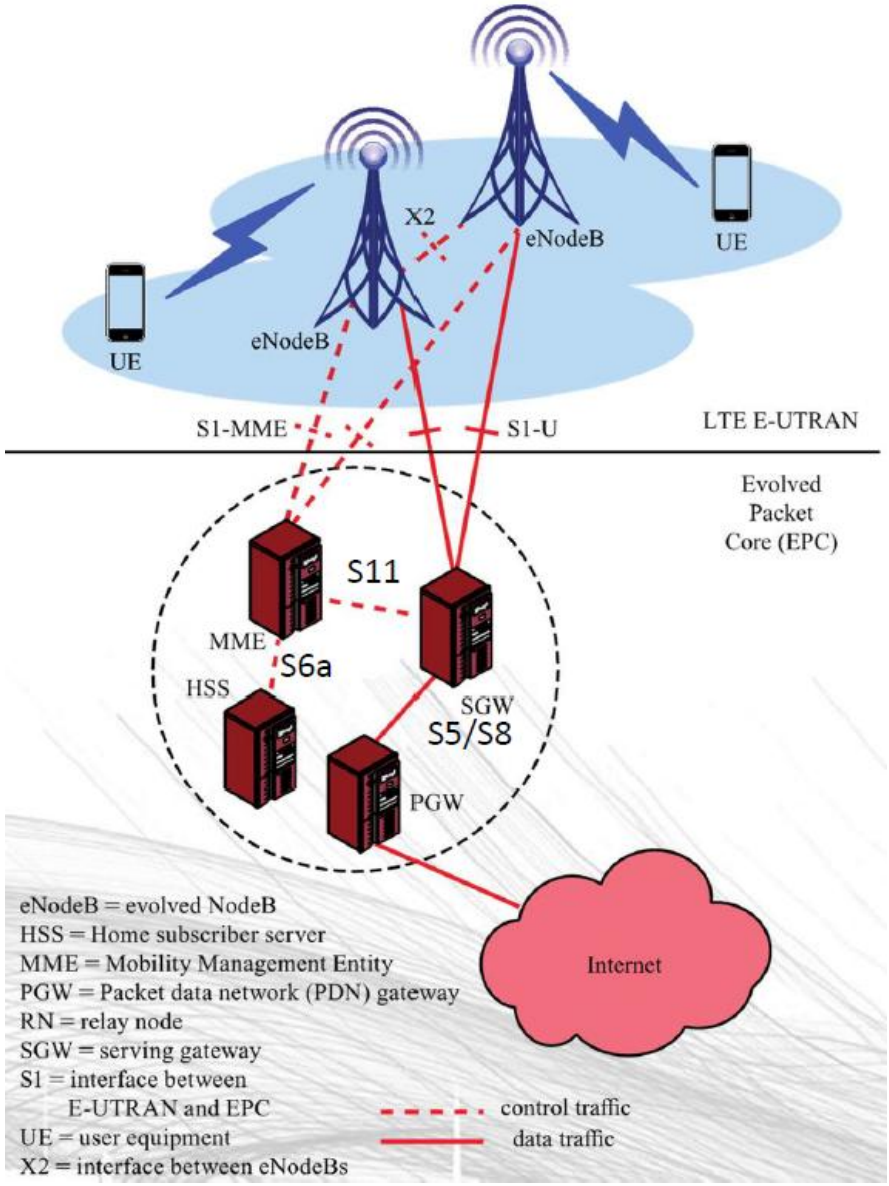
EPS functions

- Access control
  - Network selection, authentication, authorizatic[illegible] admission control
    policy and charging enforcement, lawful interc
- Packet routing
- Security
  - Encryption, integrity protection
- Mobility management
- Radio resource management
- Network management
- IP networking



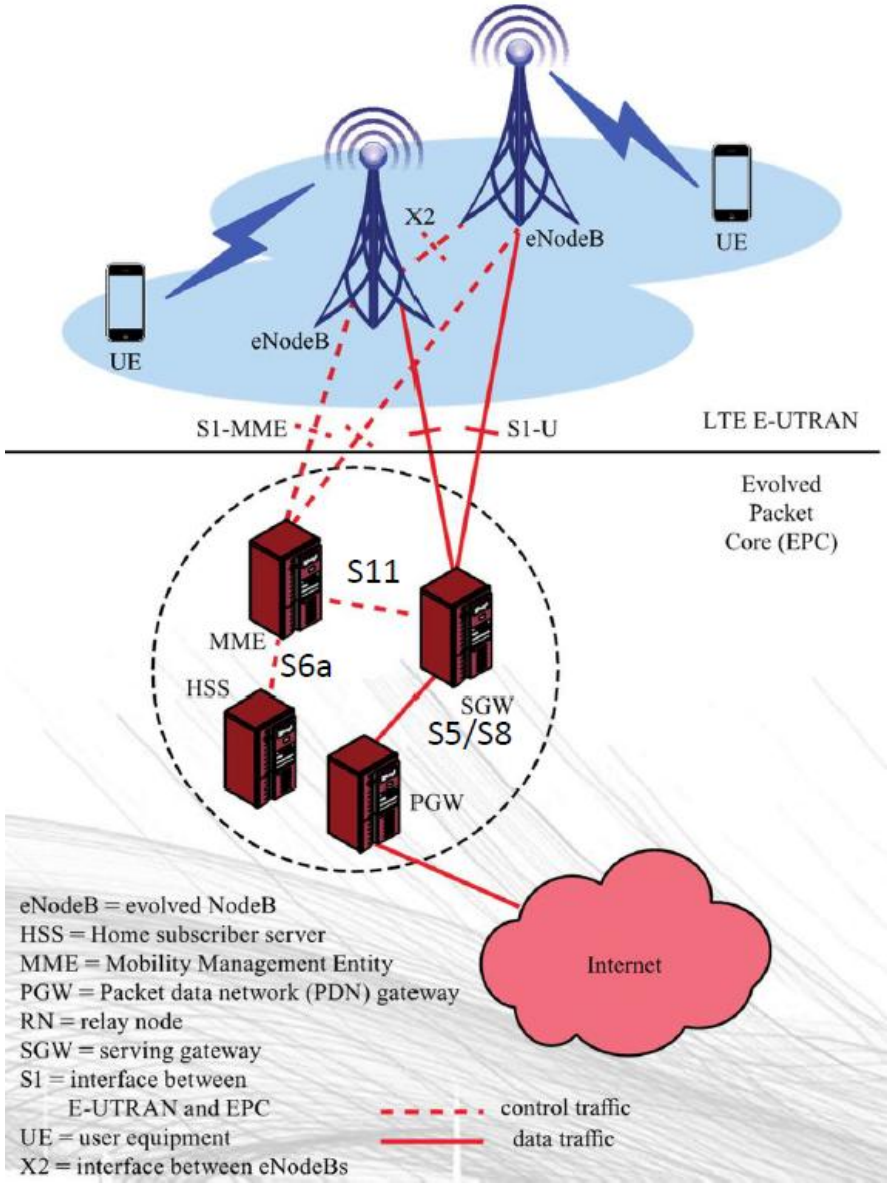
EPC components

- Mobility Management Entity (MME)
  - Supports user equipment context, identity, authentication, and authorization
  - Mainly perform Non Access Stratum procedures, which consist of two main groups
    - Functions related to bearer management (EPS Session Management)
      - Bearer can be seen as a logical communication tunnel
    - Functions related to connection management (EPS Mobility Management)



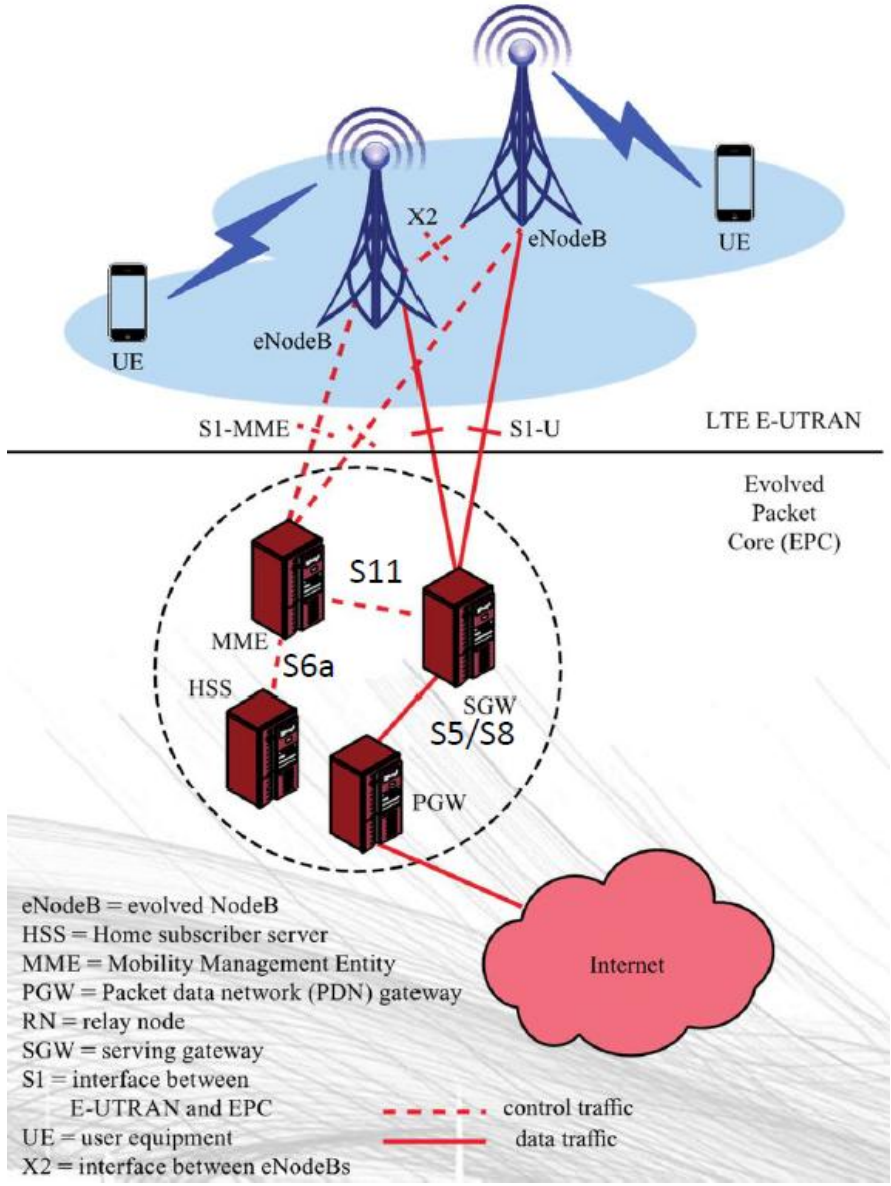
EPC components

- Serving Gateway (SGW)
  - Receives and sends packets between the eNodeB and the core network
  - Perform packet routing and forwarding within EPC
  - Anchor point for intra LTE-mobility
  - Lawful intercept



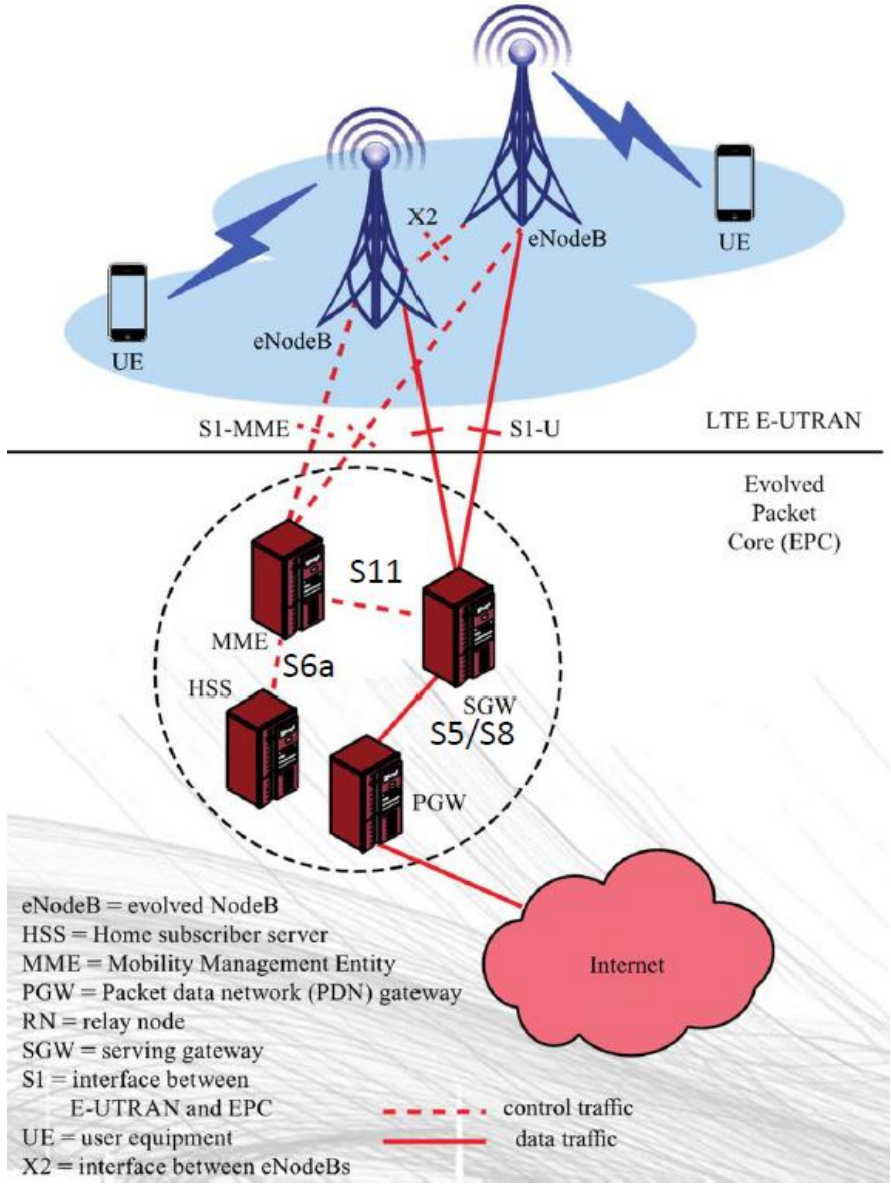
EPC components

- Packet Data Network Gateway (PGW)
  - Connects the EPC with external networks
    - Internet
    - PSTN
  - A router that performs UE IP assignment, per user packet filtering
  - Anchor point for mobility with non 3GPP access network
  - Lawful intercept



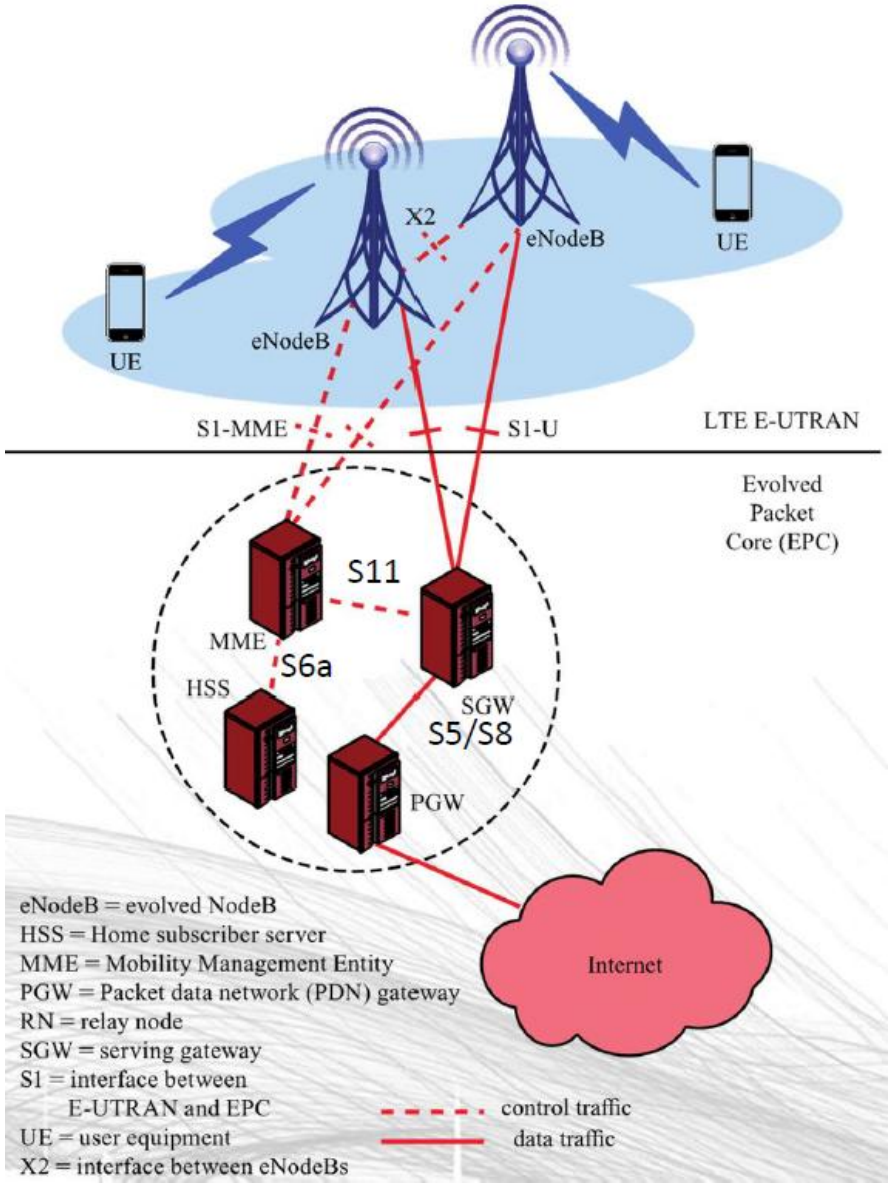
EPC components

- Home Subscriber Server (HSS)
  - Database of user-related and subscriber-related information
- Interfaces
  - S1 interface between LTE and EPC
    - For both control purposes (connect MME to eNodeB) and for user plane data traffic(connect SGW to eNodeB)
  - S5/S8 connects MME with PGW
  - S11 connects SGW with MME



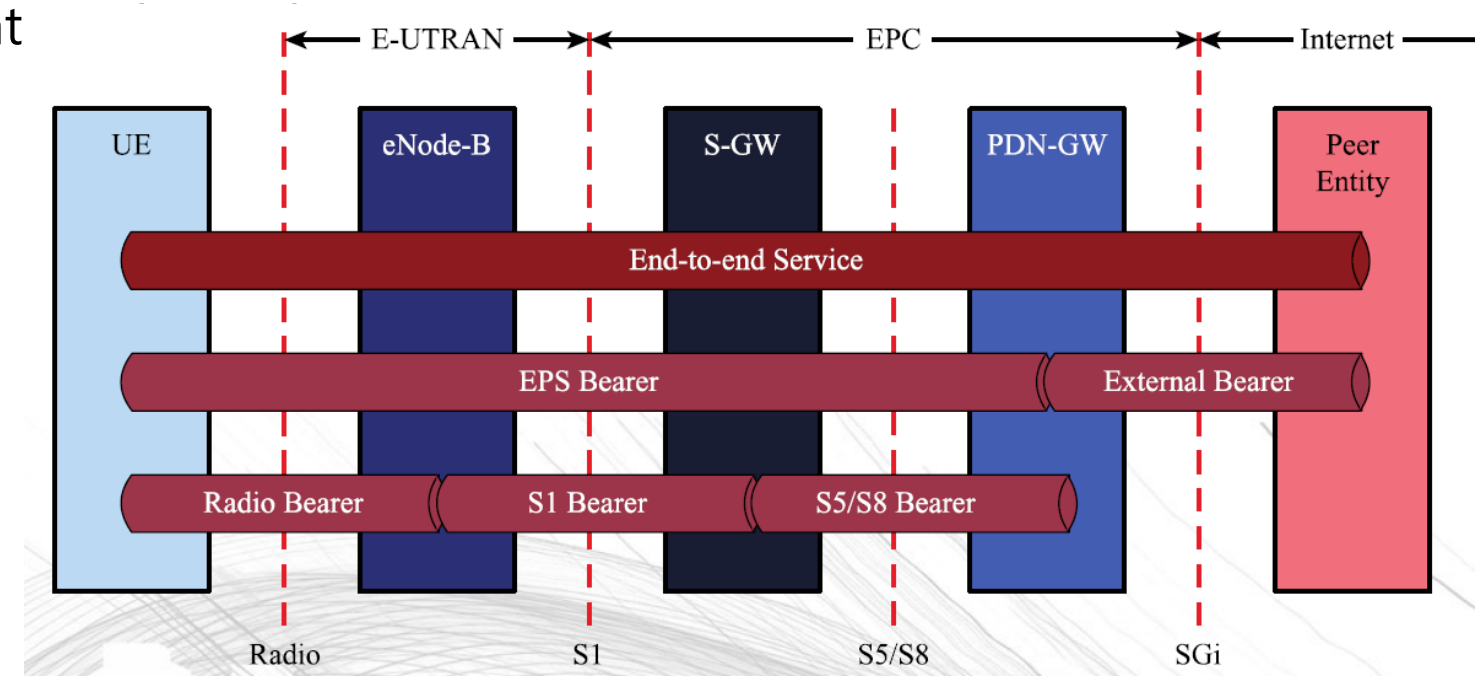
Radio access network

- Mainly consist of eNodeB's
- Runs Access Stratum Protocol (AS)
- X2 interface between eNodeB
  - X2 control and X2 user
- Main functions
  - Radio resource management
    - Radio bearer control
    - Radio mobility control
    - Scheduling (uplink and downlink)
  - Header compression
  - Security
  - Connectivity to EPC



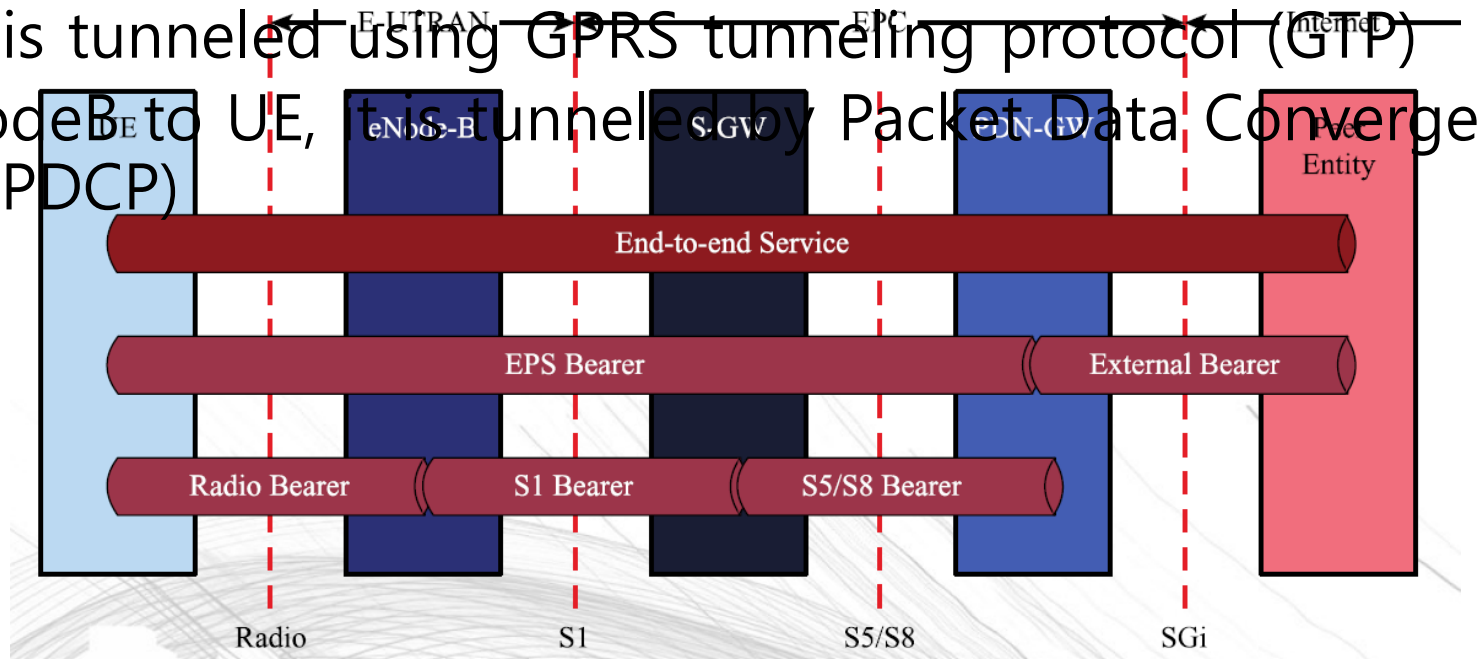
Radio resource management

- "bearer" = packet "pipe" with committed resource
  - Like circuit in circuit switching
  - Runs between PGW and UE (smartphone)
  - Can be mapped to specific QoS parameters
    - Data rat



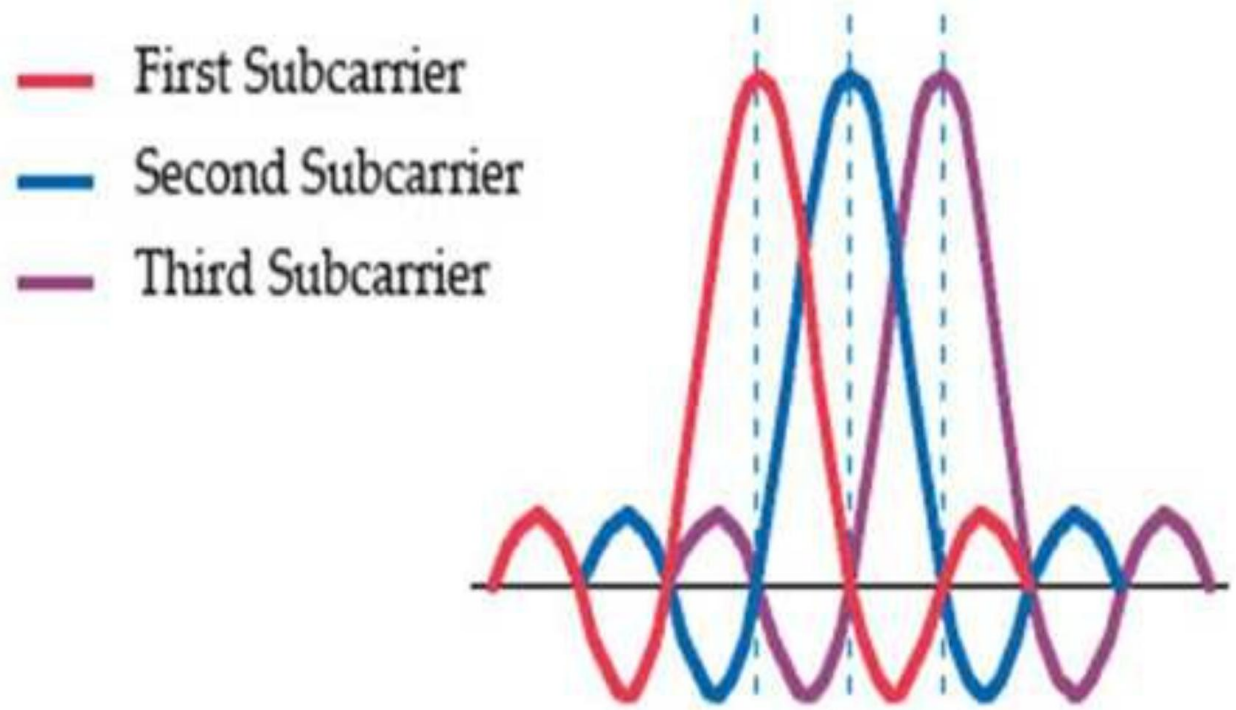
Radio resource management

- When UE connect to the EPS, a persistent, default bearer connection is established through the life time of the connection
- User plane transports IP packets between PGW and UE
  - In EPC, it is tunneled using GPRS tunneling protocol (GTP)
  - From eNodeB to UE, it is tunneled by Packet Data Convergence Protocol (PDCP)



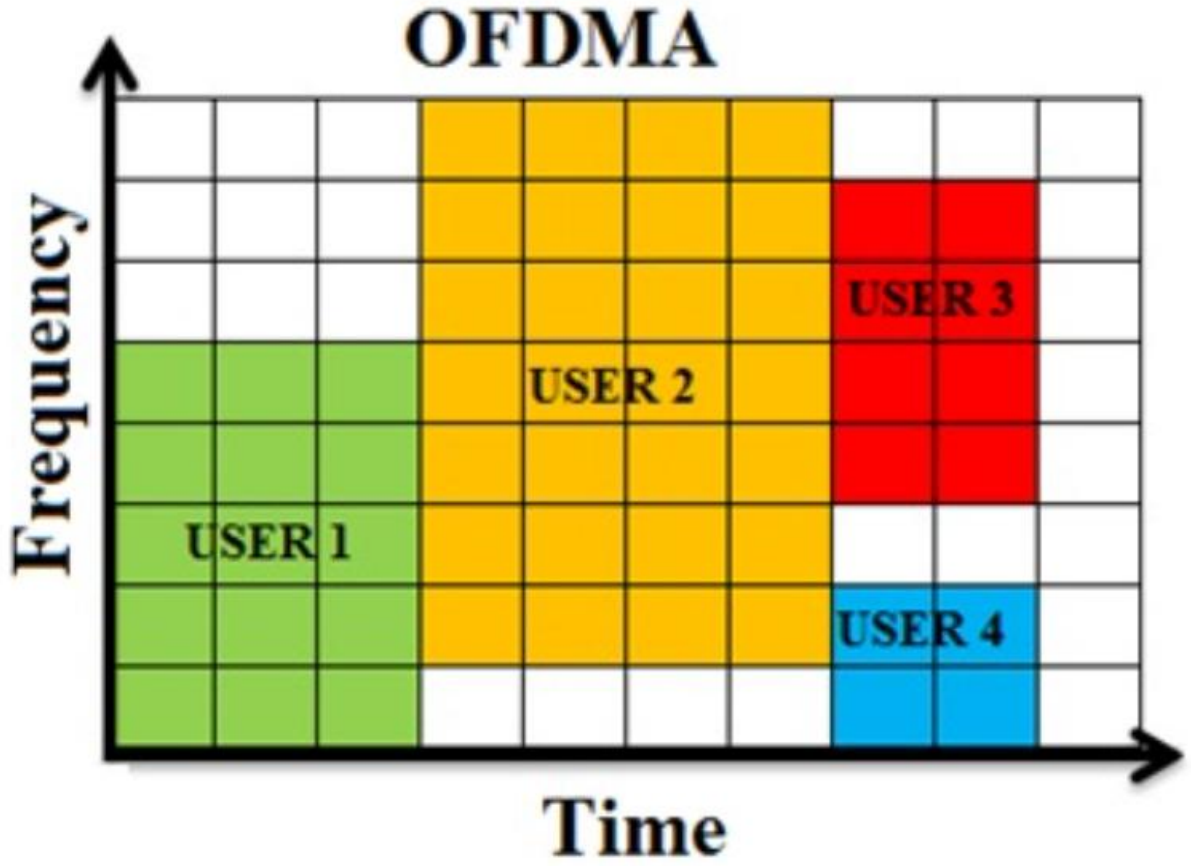
OFDM

- Orthogonality between subcarriers



OFDMA

- Very much like our classroom scheduling

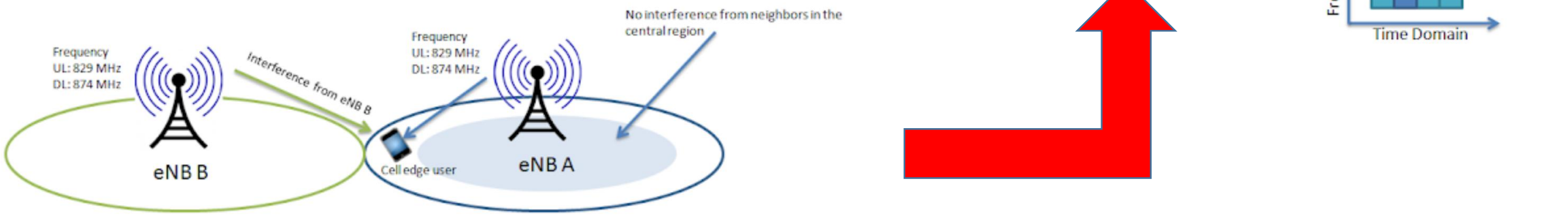


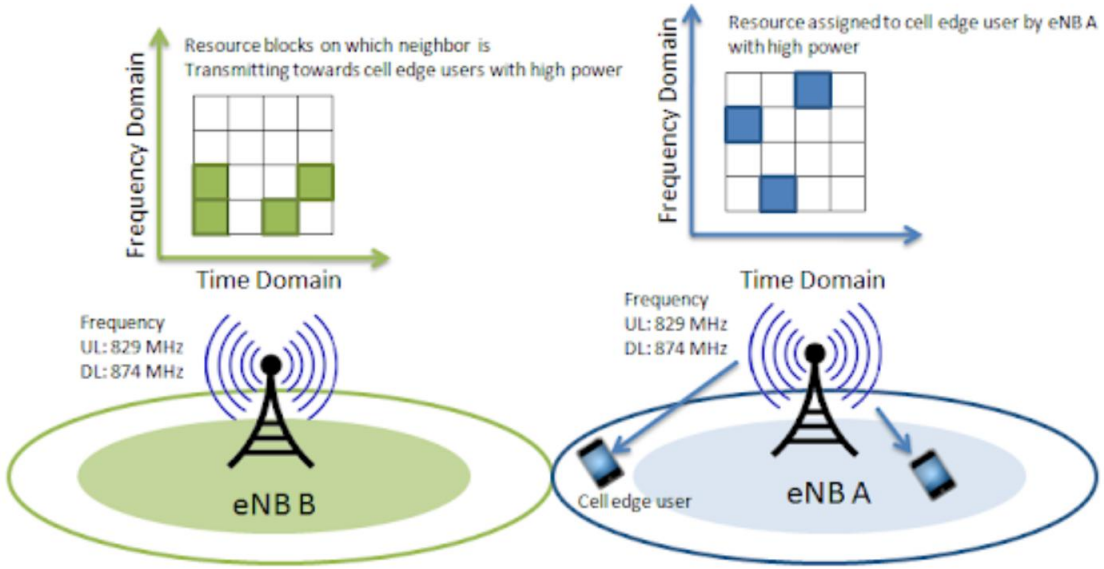
Inter-cell interference coordination (ICIC)

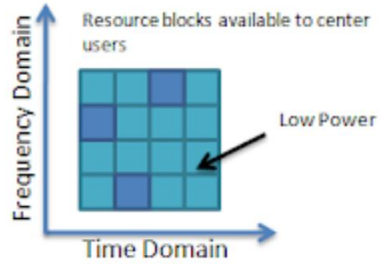
- When the same frequency is used in a neighboring cell
- Goal is universal frequency reuse (N = 1)
  - Must avoid interference when UEs are near each other at cell edges
  - Interference randomization, cancellation, coordination, and avoidance are used
- eNodeBs send indicators
  - Relative Narrowband Transmit Power, High Interference, and Overload indicators
- Later releases of LTE have improved interference control

ICIC

- User different power and frequency to mitigate inter-cell interference

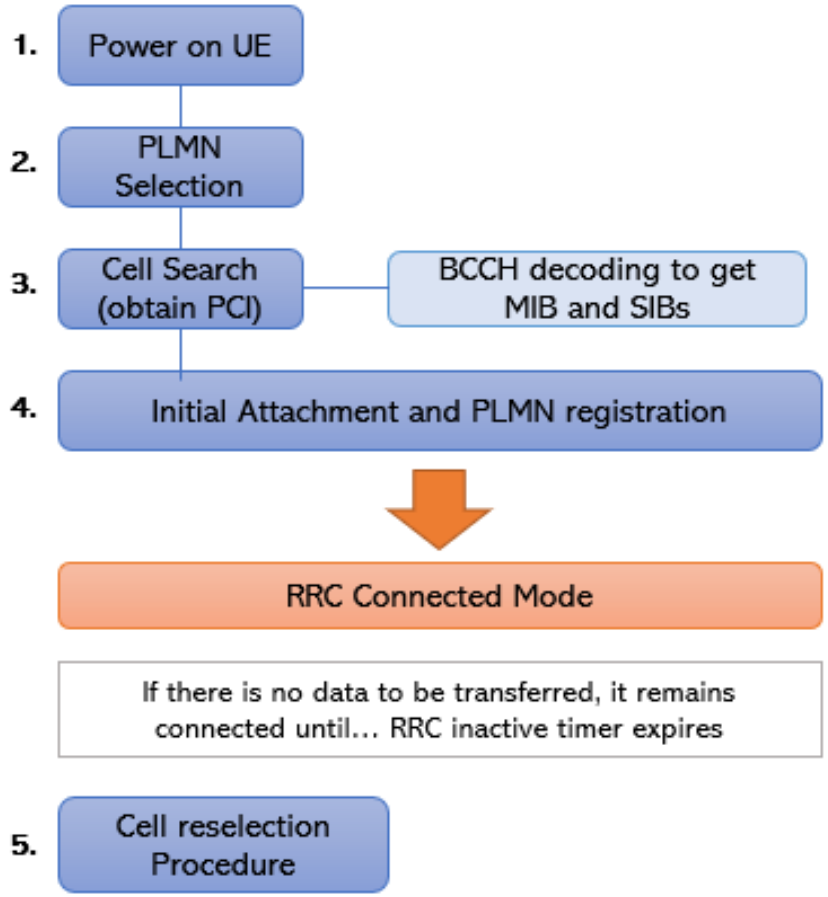






Connection procedure

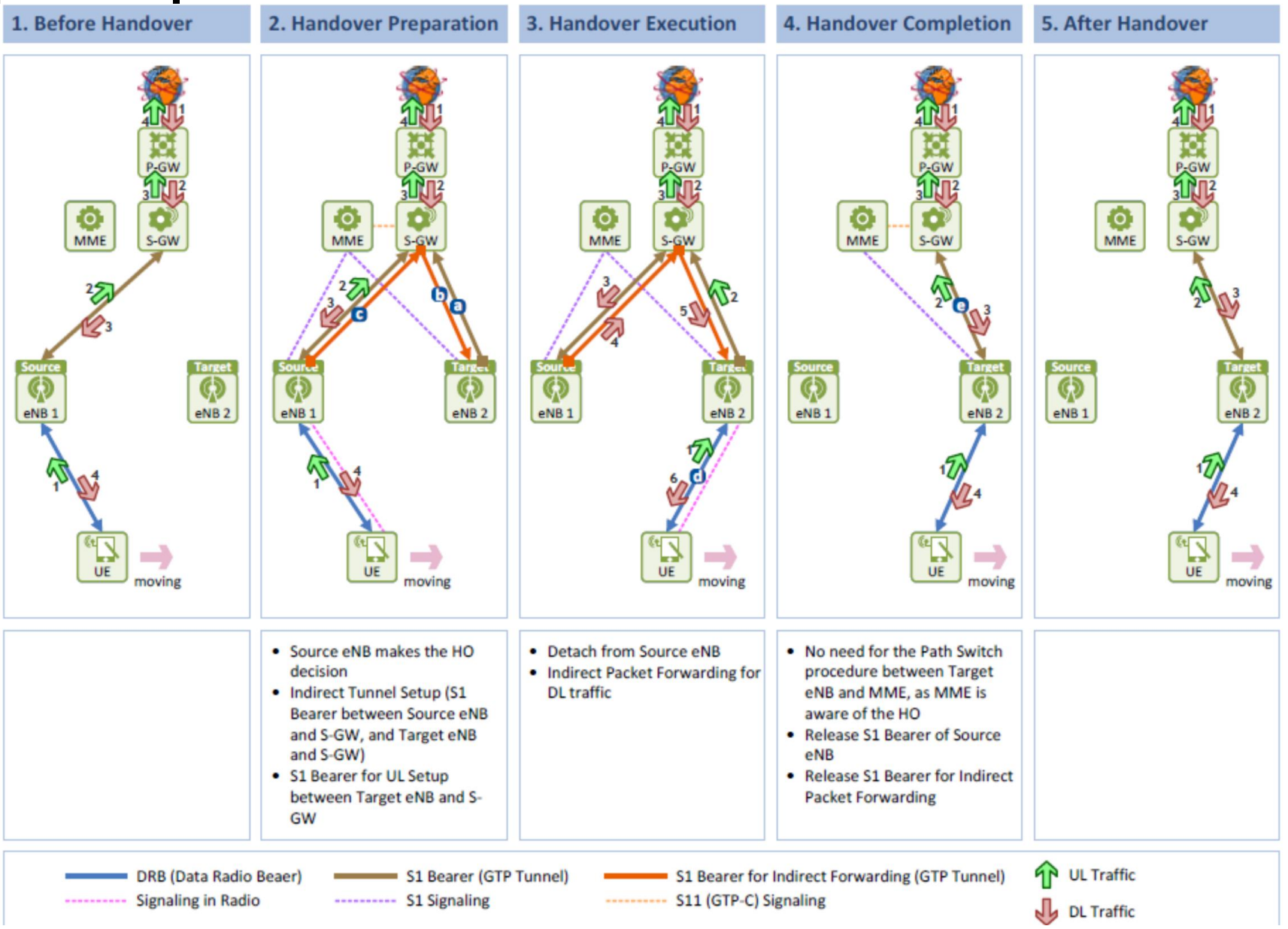
- Initially, UE (e.g. smartphone) selects Public Land Mobile Network (PLMN)
  - Look into USIM
  - Register to PLMN
- Select a cell in the PLMN
  - Last cell the UE camped on, or
  - Scan one
  - Synchronize to it
- Mobility management
  - Connected: handover
  - Idle: cell reselection



Mobility management: hard handover

- S1 mobility
  - Preparation
    - Decision has been made for handover and the destination MME and eNodeB have been identified
    - MME sends handover request to destination eNodeB
    - MME sends handover command to UE
  - Execution
    - UE performs RAN procedures for the handover
    - Involving eNodeB's exchange relevant data for handover
  - Completion
    - Target eNodeB notifies MME
    - MME directs source eNodeB to release the resources that has been used by the UE

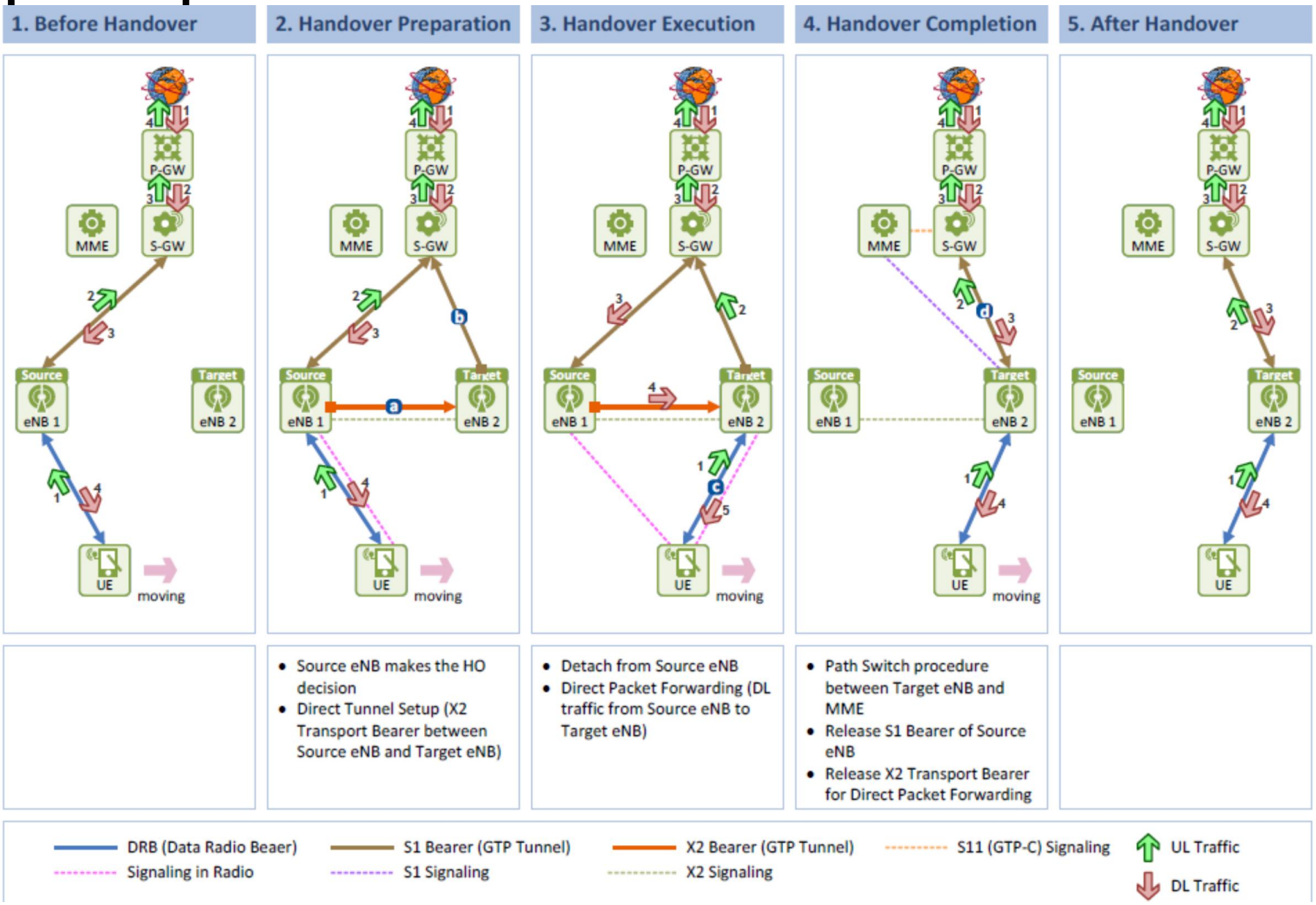
S1


1. Before Handover
2. Handover Preparation
3. Handover Execution
4. Handover Completion
5. After Handover
P-GW
MME
S-GW
Source
Target
eNB 1
eNB 2
UE
moving
• Source eNB makes the HO decision
• Indirect Tunnel Setup (S1 Bearer between Source eNB and S-GW, and Target eNB and S-GW)
• S1 Bearer for UL Setup between Target eNB and S-GW
• Detach from Source eNB
• Indirect Packet Forwarding for DL traffic
• No need for the Path Switch procedure between Target eNB and MME, as MME is aware of the HO
• Release S1 Bearer of Source eNB
• Release S1 Bearer for Indirect Packet Forwarding
DRB (Data Radio Beaer)
Signaling in Radio
S1 Bearer (GTP Tunnel)
S1 Signaling
S1 Bearer for Indirect Forwarding (GTP Tunnel)
S11 (GTP-C) Signaling
UL Traffic
DL Traffic

Mobility management

- X2 mobility
  - Preparation
    - Source eNodeB sends handover request to destination eNodeB
    - Destination eNodeB works with MME and SGW to establish resources for the UE
  - Execution
    - Source eNodeB signals the UE
    - The UE performs RAN procedures for handover
    - Data exchanges between involving eNodeB
  - Completion
    - UE sends handoff complete message to MME and SGW
    - SGW switch GTP tunnel to the destination eNodeB
    - Destination eNodeB asks source eNodeB to release the resource for the UE

X2

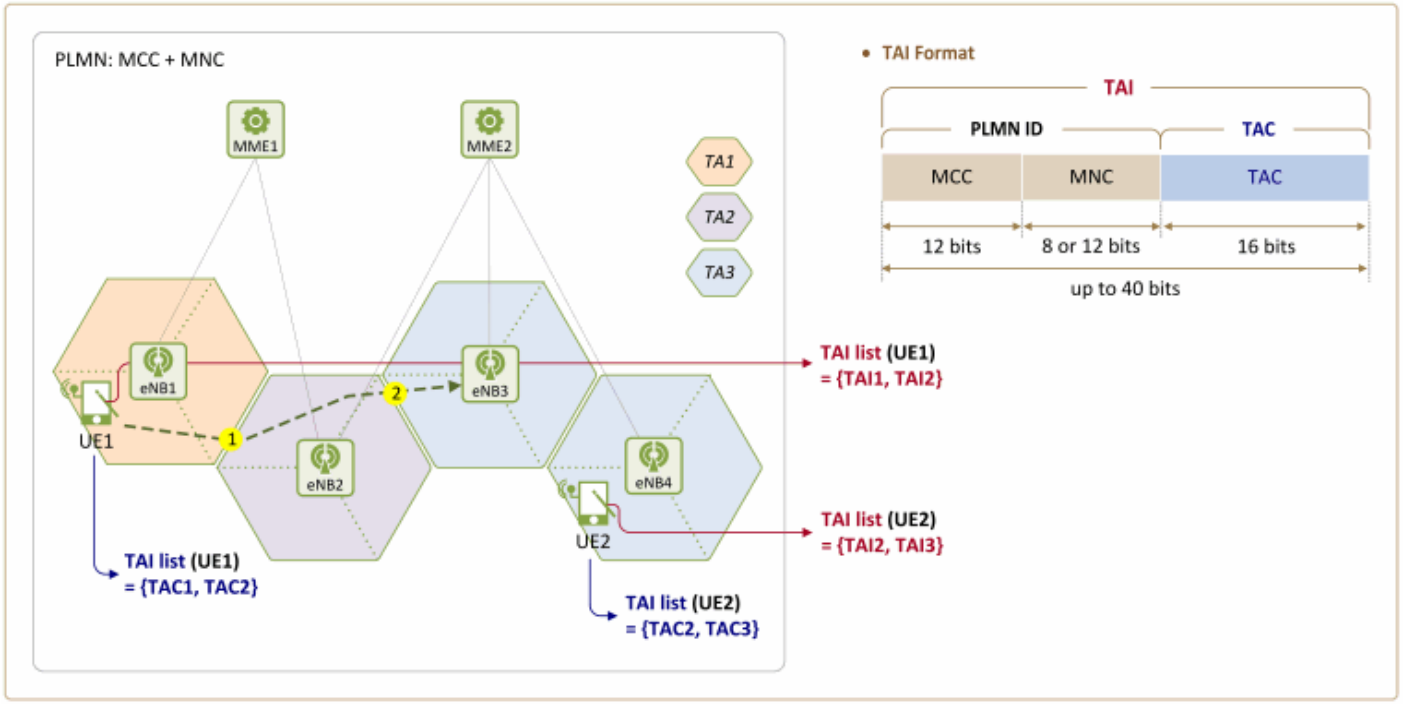

1. Before Handover
2. Handover Preparation
3. Handover Execution
4. Handover Completion
5. After Handover
P-GW
MME
S-GW
Source
eNB 1
Target
eNB 2
UE
moving
• Source eNB makes the HO decision
• Direct Tunnel Setup (X2 Transport Bearer between Source eNB and Target eNB)
• Detach from Source eNB
• Direct Packet Forwarding (DL traffic from Source eNB to Target eNB)
• Path Switch procedure between Target eNB and MME
• Release S1 Bearer of Source eNB
• Release X2 Transport Bearer for Direct Packet Forwarding
DRB (Data Radio Beaer)
Signaling in Radio
S1 Bearer (GTP Tunnel)
S1 Signaling
X2 Bearer (GTP Tunnel)
X2 Signaling
S11 (GTP-C) Signaling
UL Traffic
DL Traffic

Mobility procedure

- To determines handover decisions, following information might be included
  - Radio link quality, UE capability, call type, QoS requirements, and policy related aspects
    - Reference Signal Received Power (RSCP) indicates radio link quality for a connection in an LTE cell
  - UE prepares measurement report which contains RSCP for the neighboring eNodeBs
    - The serving eNodeB provides the list of eNodeB as requested by the UE

Mobility management

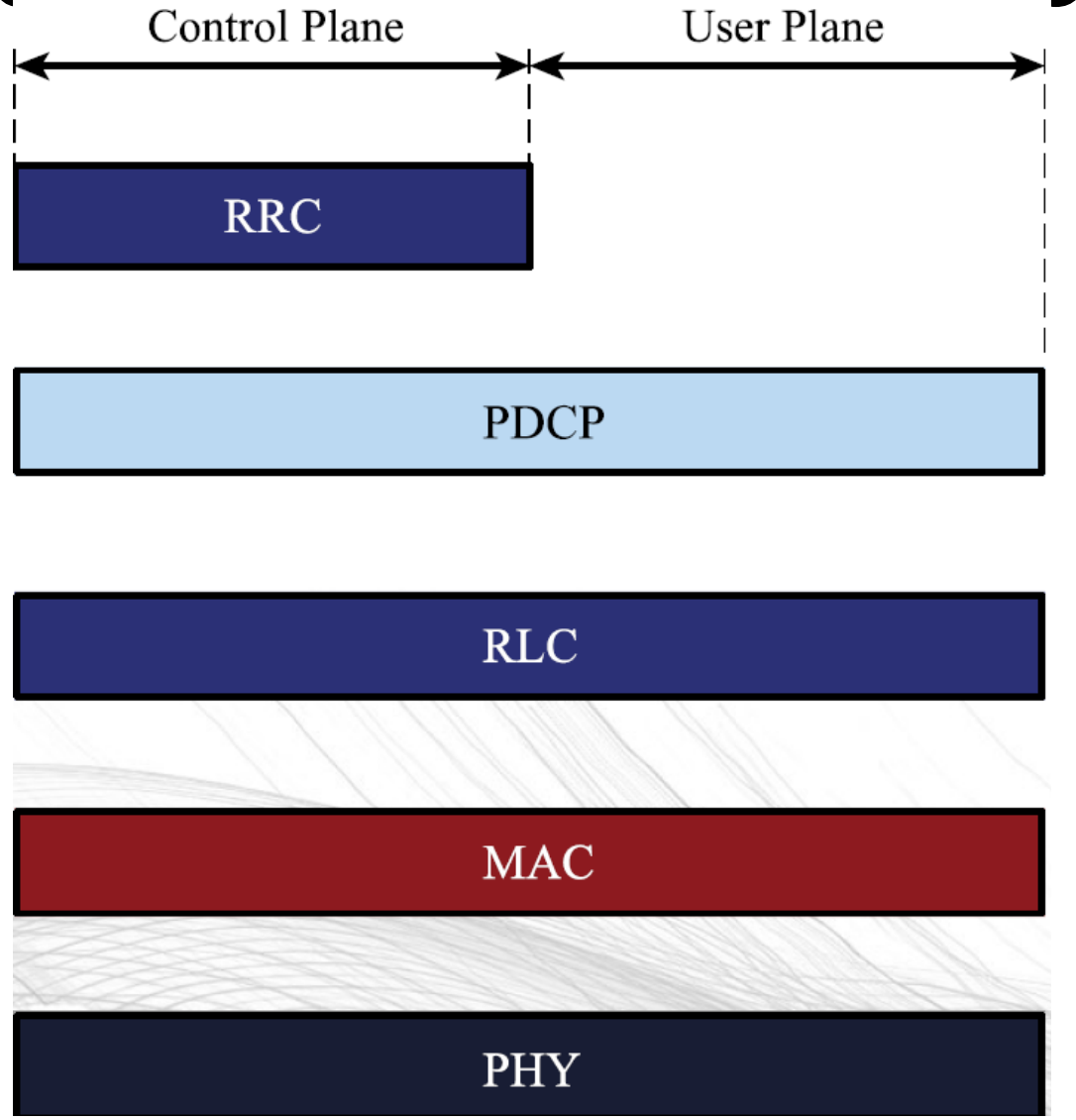
- Cell reselection is mobility management for idle terminals
  - Idle terminal periodically wakes up and measures signal power from its current serving cell
- In case the mobility crosses tracking area (TA) boundary, update this information
  - For paging later



LTE channel structures and protocols

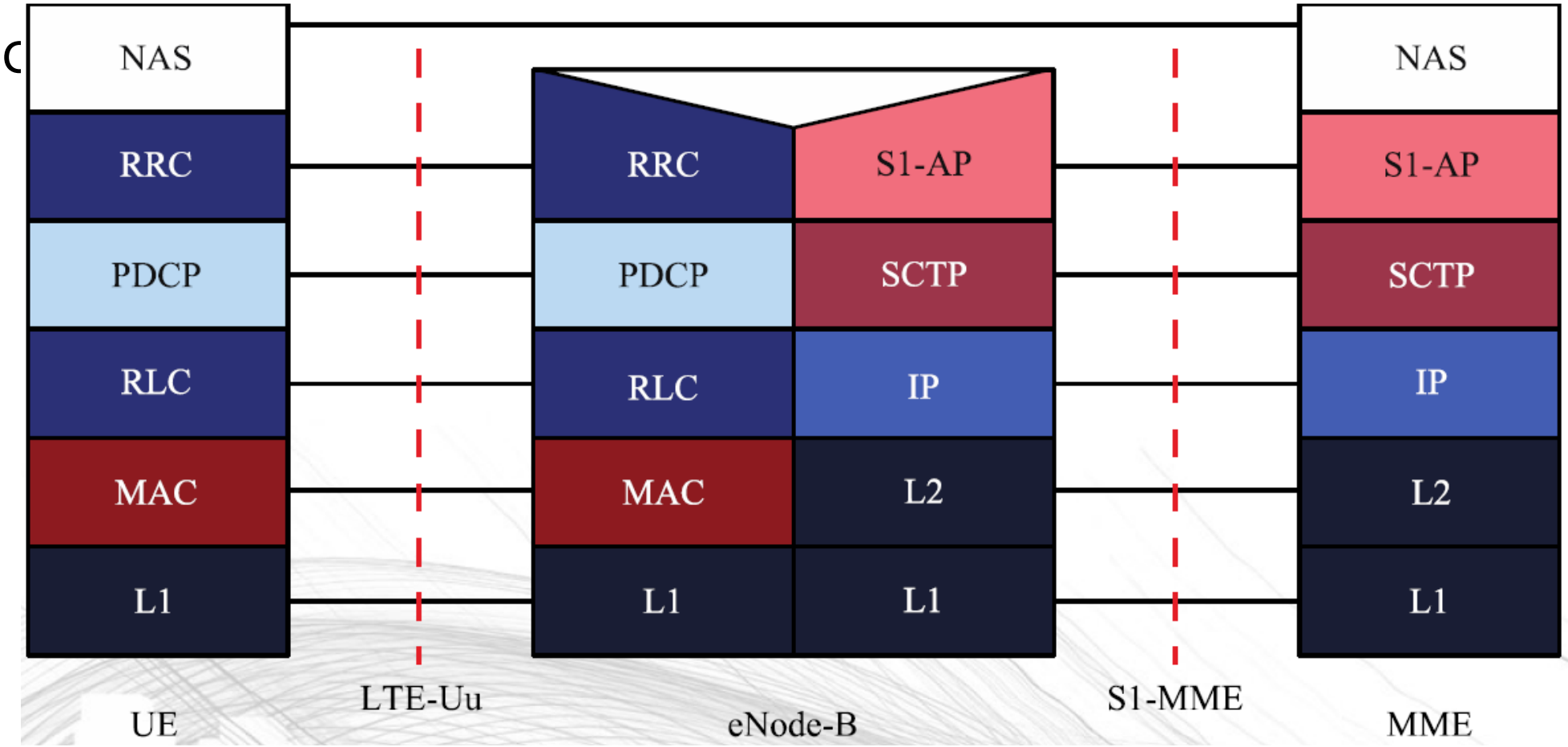
- LTE radio interface is divided
  - Control Plane
  - User Plane
- User plane protocols
  - Part of the Access Stratum
  - Transport packets between UE and PGW
  - PDCP transports packets between UE and eNodeB on the radio interface
  - GTP sends packets through the other interfaces
- Control plane protocols
  - Part of Non-Access Stratum (NAS) for communication between MME and UE
  - Deals with mobility management, call setup, security functions between UE and MME

LTE channel structures and protocols



LTE channel structures and protocols

- Cc



Control plane protocols

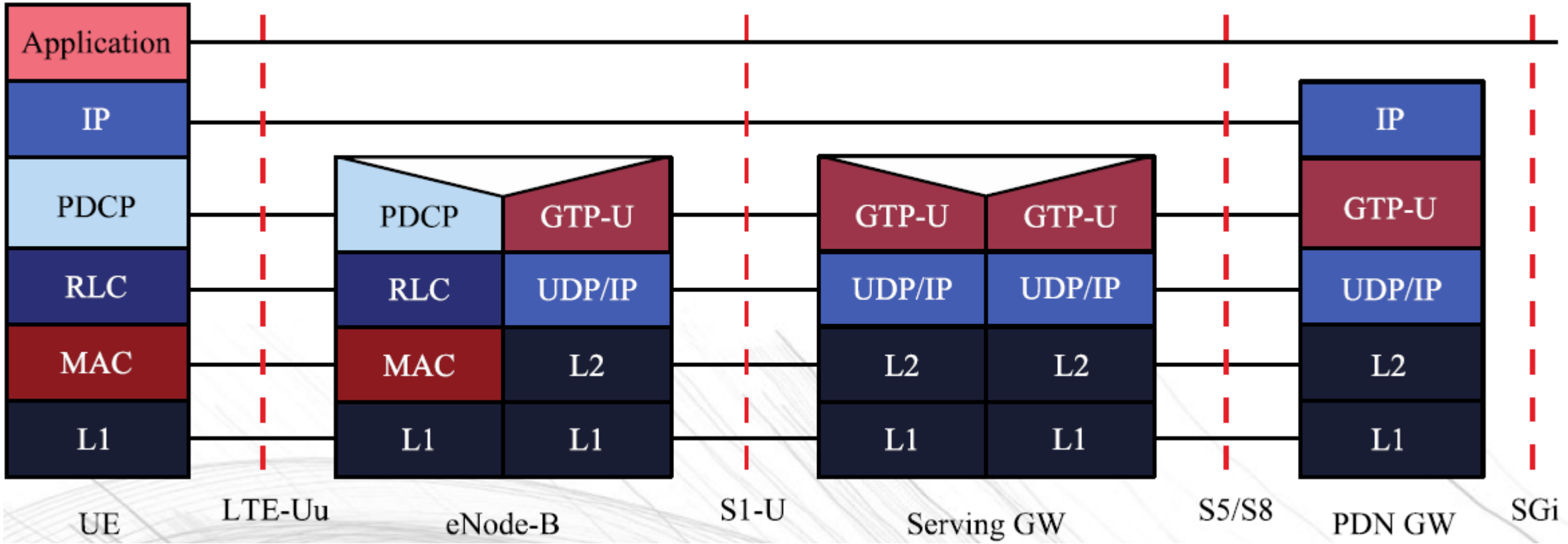
- NAS (Non Access Stratum)
  - Mobility management, call setup, security functions between UE and MME
- Radio Resource Control (RRC)
  - Performs control plane functions to control radio resources
  - Important aspects of RRC
    - Connection states :RRC_IDLE and RRC_CONNECTED states
    - Signaling Radio Bearers (SRB): Radio bearer to transmit RRC and NAS messages
    - System Control Information : Master Information Block and System Information Block
      - MIB and SIB contains essential information that UE needs to know about a cell characteristics

Non-Access Stratum (NAS) protocols

- For interaction between the EPC and the UE
  - Not part of the Access Stratum that carries data
- EPS Mobility Management (EMM)
  - Manage the mobility of the UE
- EPS Session Management (ESM)
  - Activate, authenticate, modify, and de-activate user-plane channels for connections between the UE, SGW, and PGW

LTE channel structures and protocols

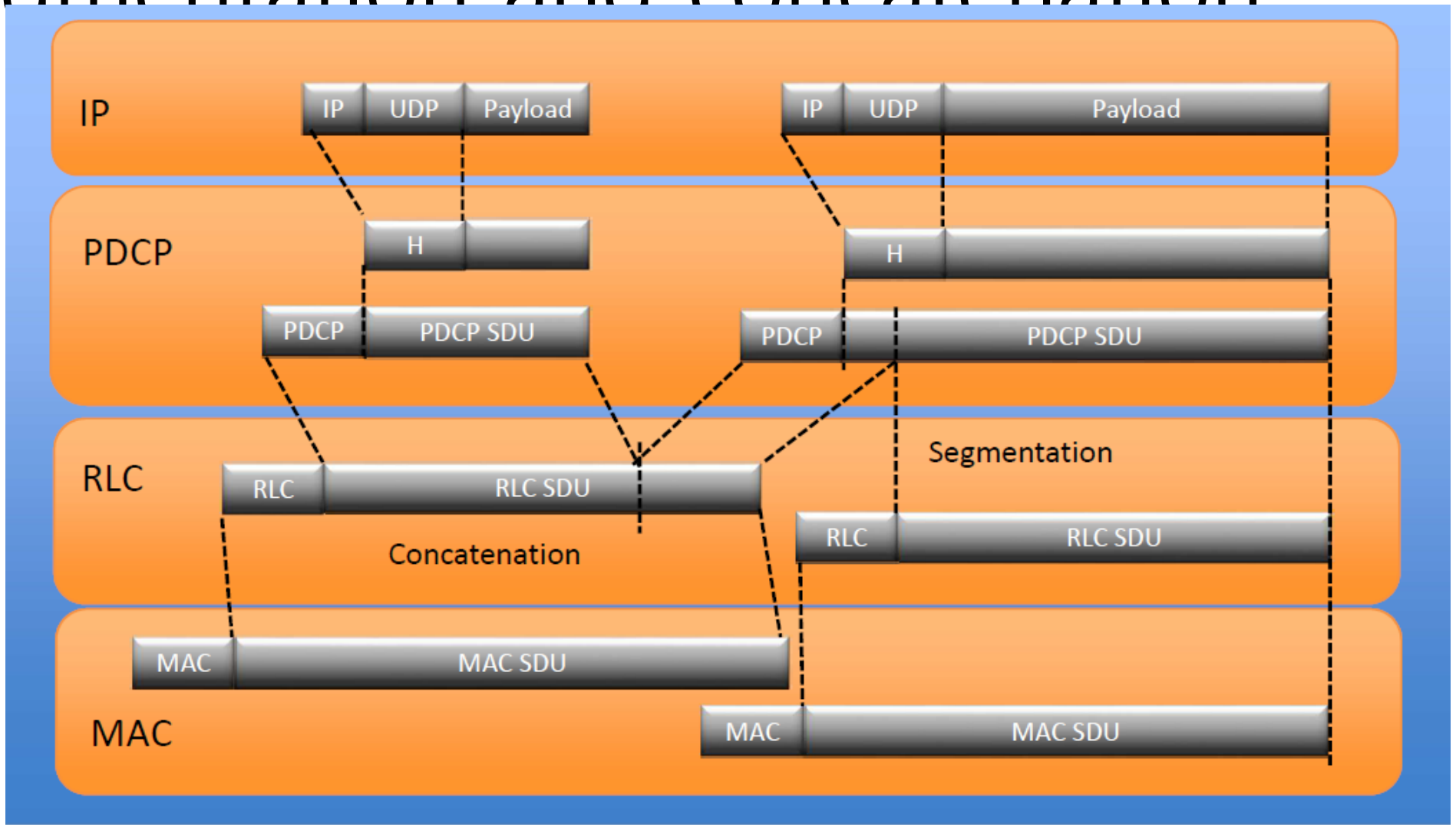
- User plane



User and control planes

- Packet Data Convergence Protocol (PDCP)
  - Delivers packets from UE to eNodeB
  - Involves header compression, ciphering, integrity protection, in-sequence delivery, buffering and forwarding of packets during handover
  - One PDCP instance per bearer
- Radio Link Control (RLC)
  - Segments or concatenates data units
  - Performs ARQ when MAC layer H-ARQ fails
  - RLC operation modes:
    - Transparent mode (TM): No header with no RLC functions for segmentation or concatenation. Used for broadcast and paging message, not for user plane data transmission
    - Unacknowledged Mode (UM) : Provides in-sequence delivery of data, no retransmission
    - Acknowledged Mode (AM) : Best for error sensitive application

Segmentation and concatenation



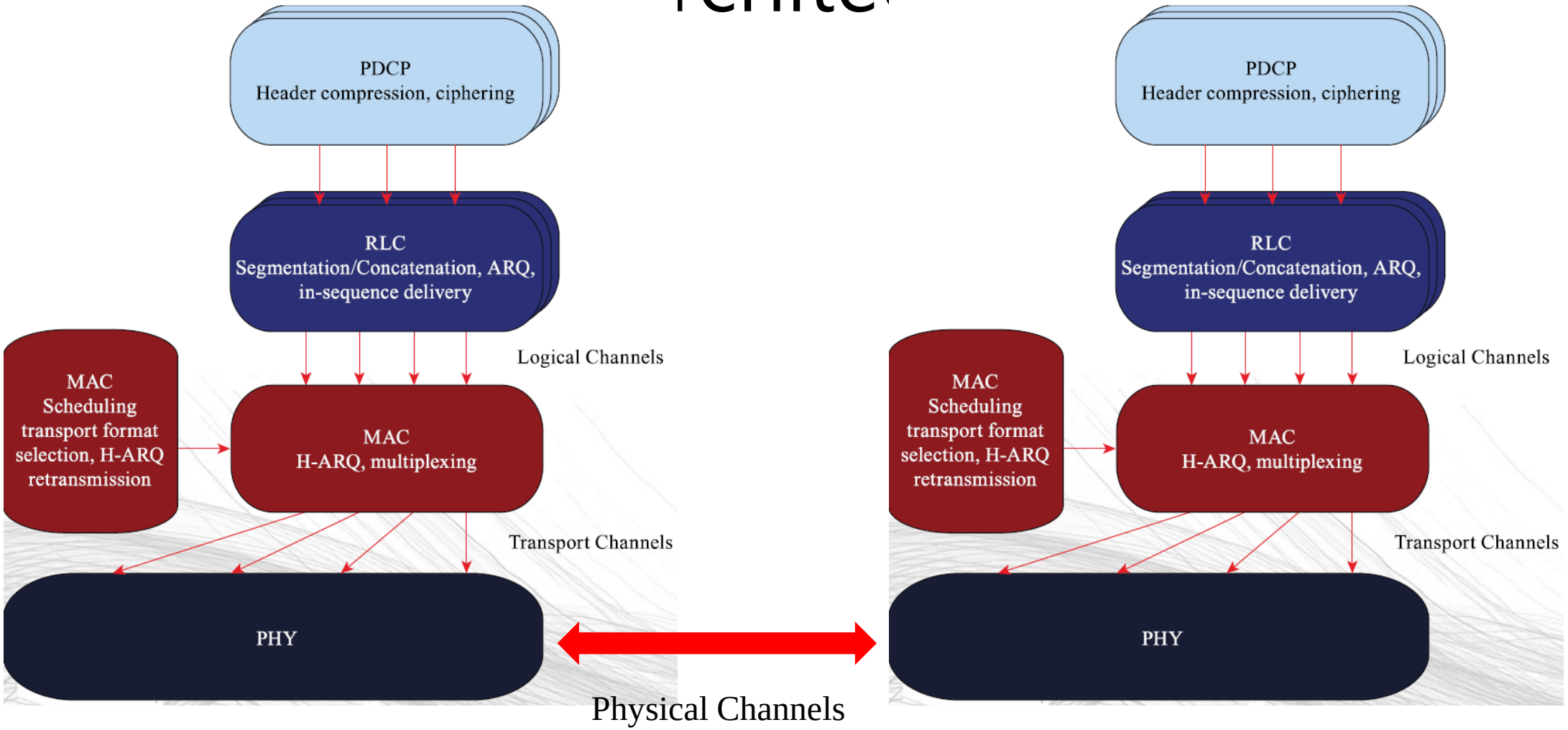
User and control planes

- Medium Access Control (MAC)
  - Performs H-ARQ
  - Prioritizes and decides which UEs and radio bearers will send or receive data on which shared physical resources
  - Decides the transmission format, i.e., the modulation format, code rate, MIMO rank, and power level
- Physical layer actually transmits the data

LTE channel structure

- Three types of channels
  - Channels provide services to the layers above
  - Defined at the Service Access Points between protocol layer
  - Type of channels
    - Logical channels
      - Provide services from the MAC layer to the RLC
      - Provide a logical connection for control and traffic
    - Transport channels
      - Provide PHY layer services to the MAC layer
      - Define modulation, coding, and antenna configurations
    - Physical channels
      - Define time and frequency resources use to carry information to the upper layers
- Different types of broadcast, multicast, paging, and shared channels

Radio interface architecture



Satellite communication



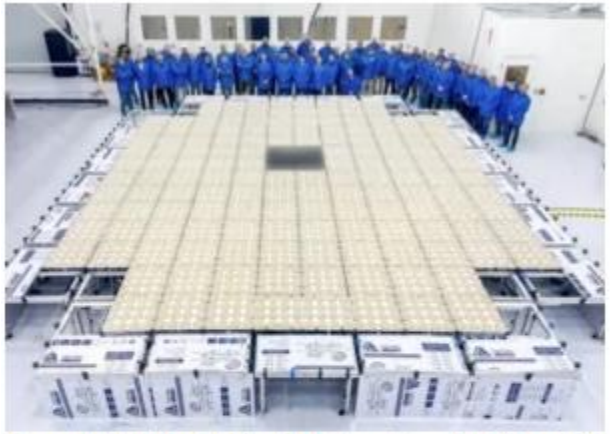
Now it’s even available to your phone

- Without modifying your phone





Starship prototypes serve as a backdrop for T-Mobile's Mike Sievert and SpaceX's Elon Musk. (T-Mobile Photo)

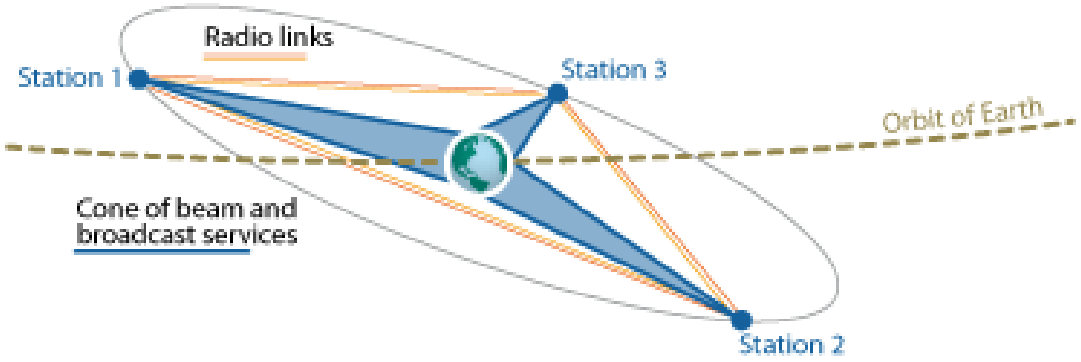


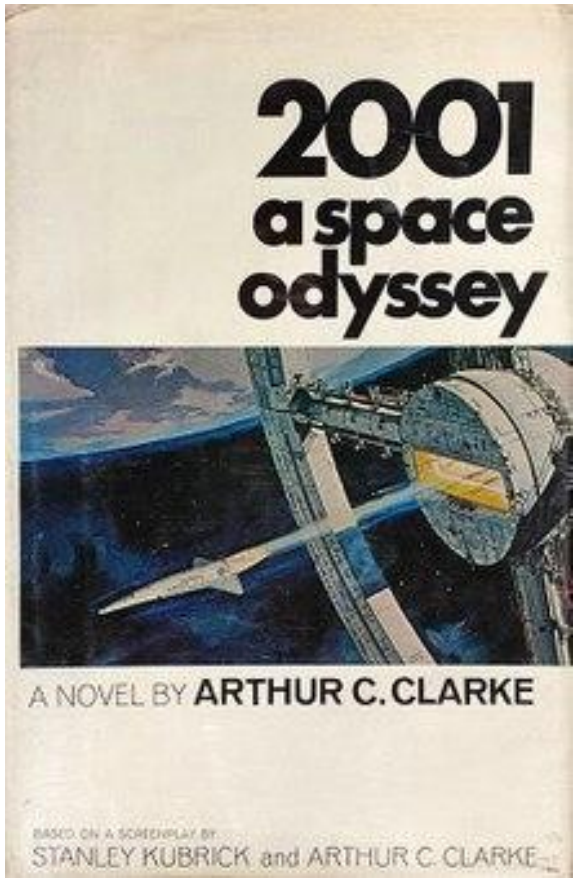
SpaceMobile's BlueWalker 3 satellite will deploy this gigantic 693 square foot antenna to enable communications with existing cellular phones. For global coverage - SpaceMobile says it will need 100+ satellites this large.

Some interesting vision from a novelist

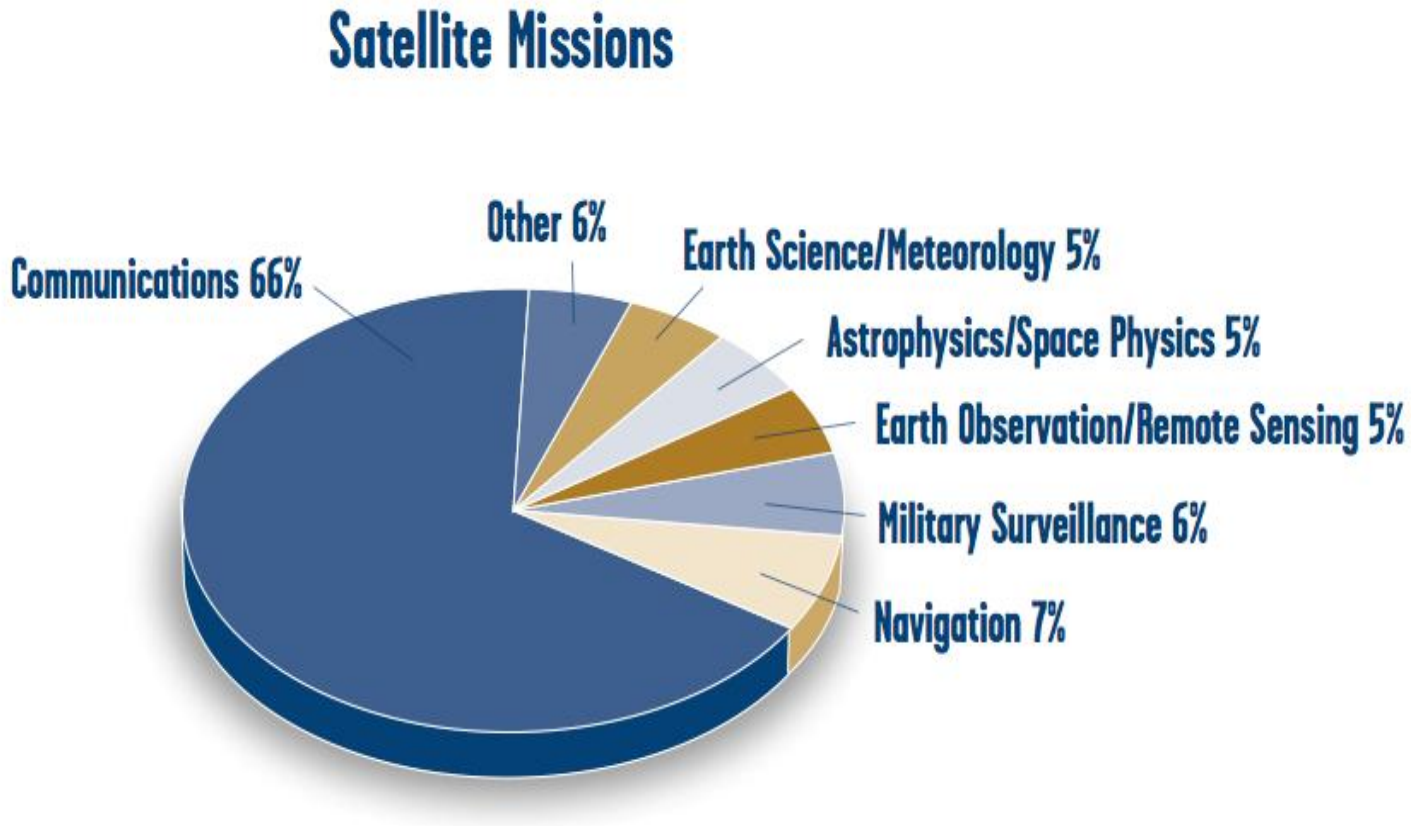
With all due respect to engineers …

- Arthur C. Clark (1917 – 2008)
  - Postulated the entire concept of international satellite telecommunications from geostationary satellite orbit including coverage, power, services, solar eclipse
    - "Extra-Terrestrial Relays", Wireless World, 1945

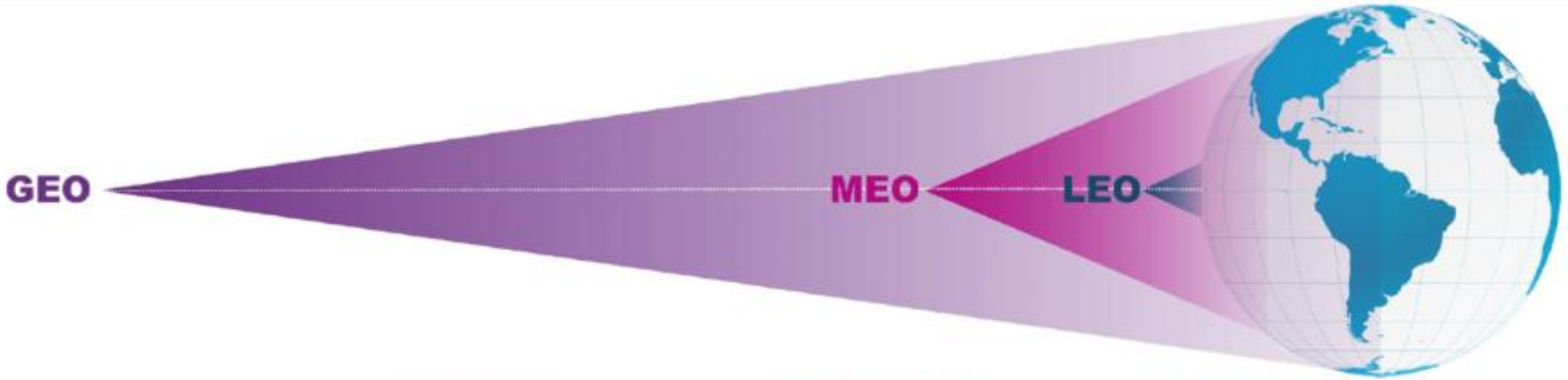




Satellite missions



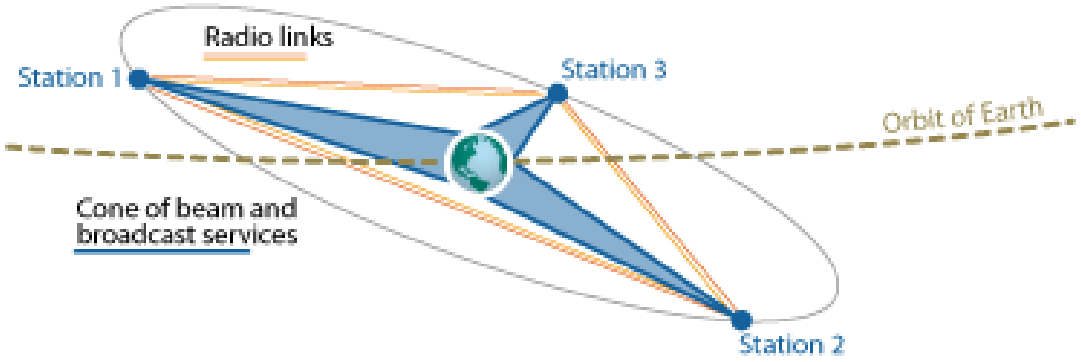
GEO, MEO, and LEO



	GEO (~36,000 km)	MEO (~8,000 km)	LEO (~1,000 km)
Latency	Medium (~700 m/s)	Low (~150 m/s)	Very low (~50 m/s)
Network size for global services	3 satellites (99% coverage)	6 satellites (96% coverage)	Thousands of satellites (100% coverage)
Data gateways required	Few, fixed	Several, flexible	Numerous, local
Technology readiness level	Proven, deployable technology	Proven, deployable technology	Technology still in development for satellite internet
Cost to deploy network	$1 - 1½bn	Approx. $1½bn	$5 - 15bn
Satellite design life (replacement cycle)	15 years	12 years	5 - 7 years

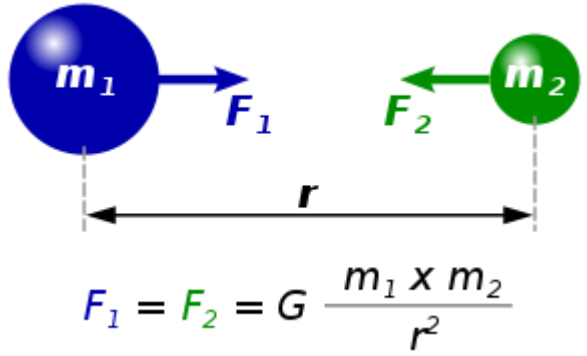
GEO

- Satellites can relay signals over a long distance
- Geostationary satellites
  - Remain above the equator at a height of about 22300 miles (geosynchronous orbits)
  - Travel around the earth in exactly the same time, the earth takes to rotate



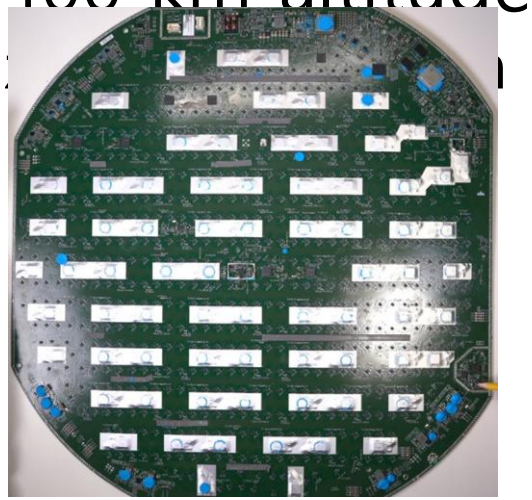
Kepler's Law and GEO

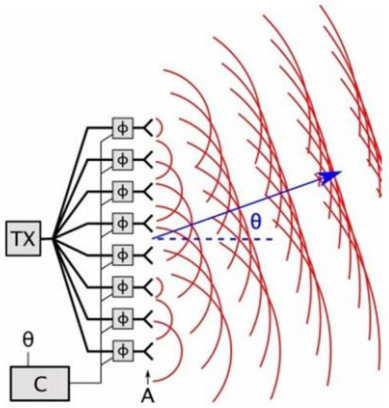
- $T^2 \left(\frac{GM_{earth}}{4\pi^2}\right) = R^3$
  - T: time for one complete orbit = 24 hours
  - G: universal gravitational constant = $6.673 \times 10^{-11} Nm^2/kg^2$
  - M_{earth}: mass of Earth = $5.9742 \times 10^{24} kg$
  - R: orbital radius (from the center of Earth) = 36,000 km



LEO

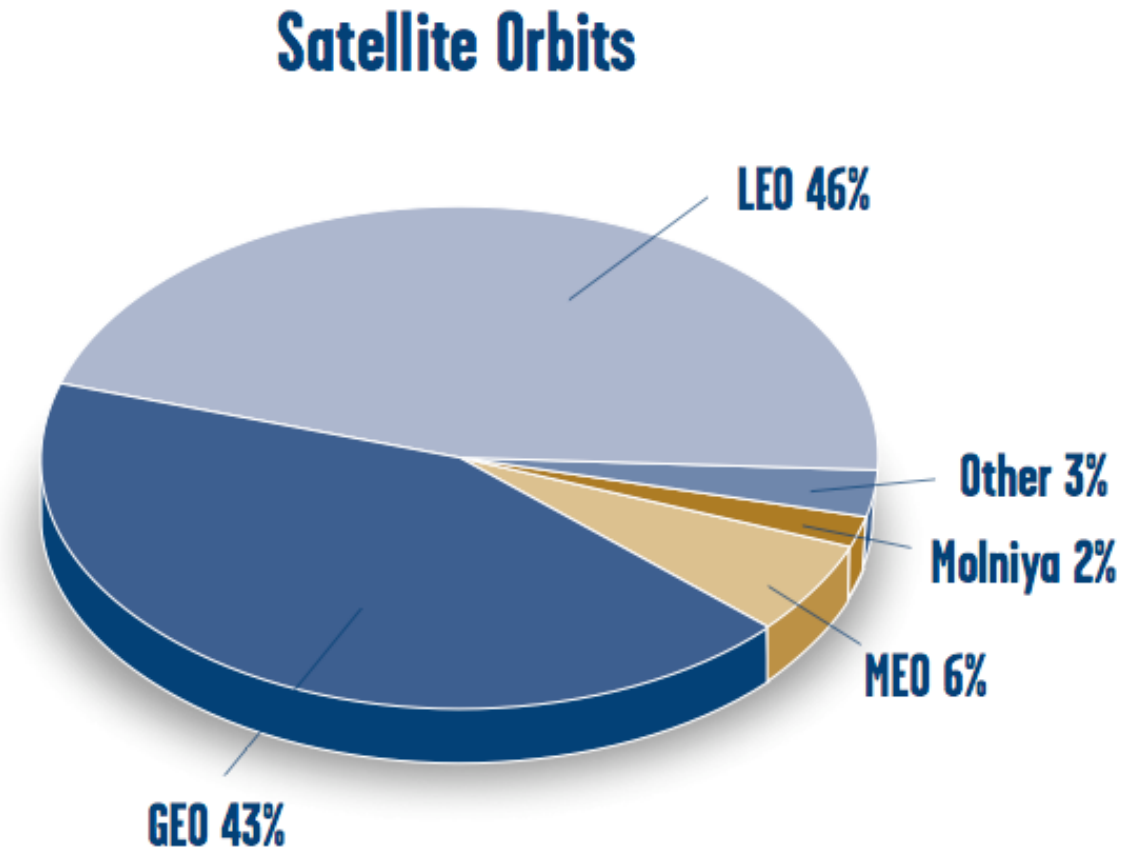
- Circular or inclined orbit with < 1400 km altitude
  - Satellite travels across sky from hori… 5 → needs handoff
  - Earth stations must track satellite
    - Phased array antenna





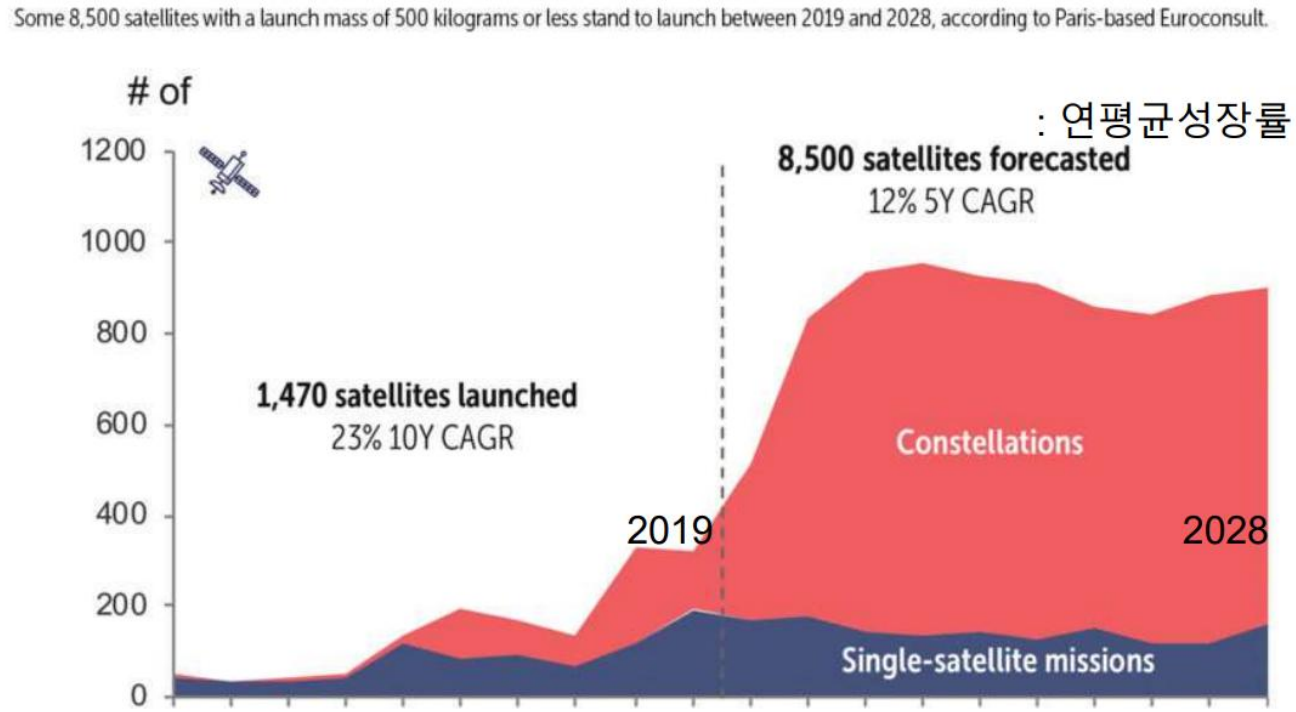
  - Large constellation of satellites is needed for continuous communication
    - 66 satellites needed to cover earth
    - 42,000 planned by Starlink

GEO, MEO, and LEO



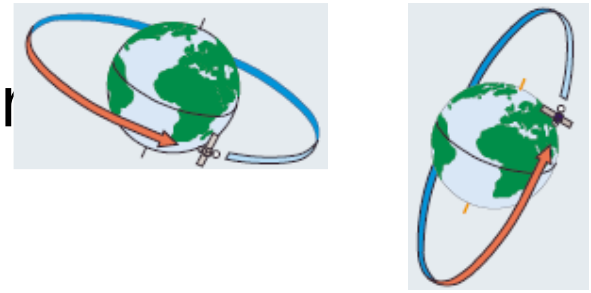
GEO, MEO, and LEO

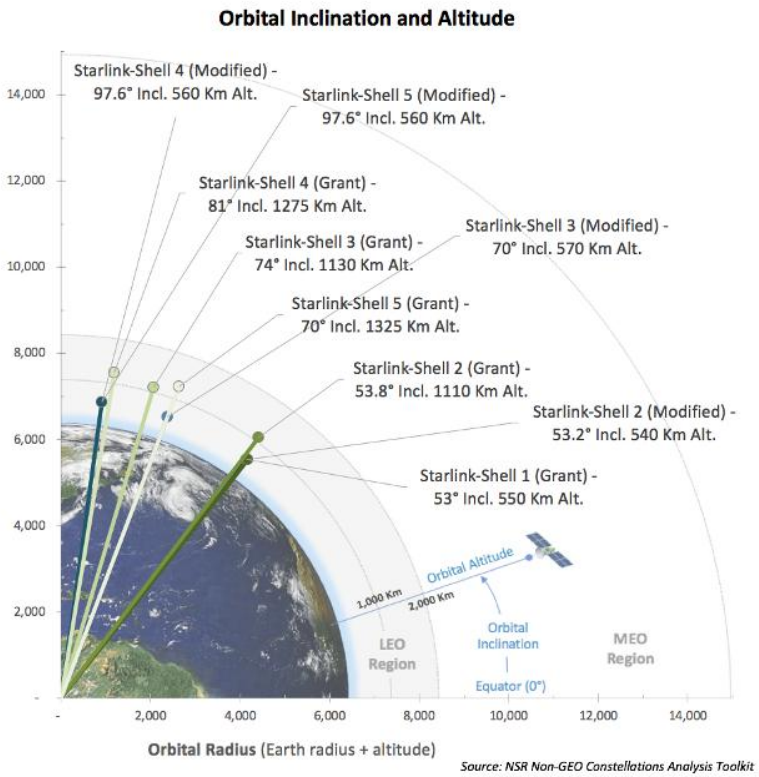


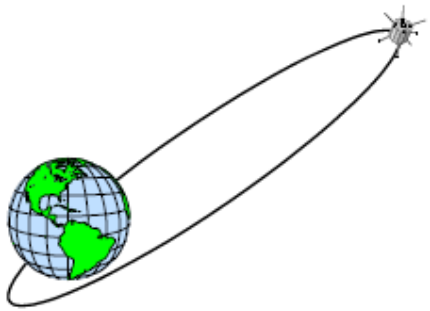


Types of orbits

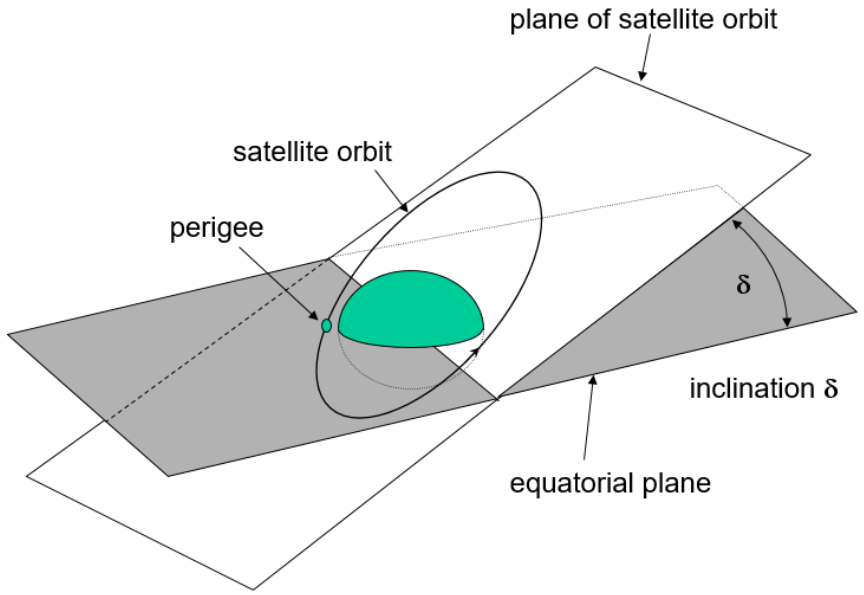
- Based on the inclination, i, over the equator
  - Equatorial Orbits above Earth's equator (i=0°)
  - Polar Orbits pass over both poles (i=90°)
  - Other orbits called inclined orbits (0°<i<90°)
    - E.g. Starlink
- Based on eccentricity
  - Circular with centre at the earth's centre
  - Elliptical with one foci at earth's centre

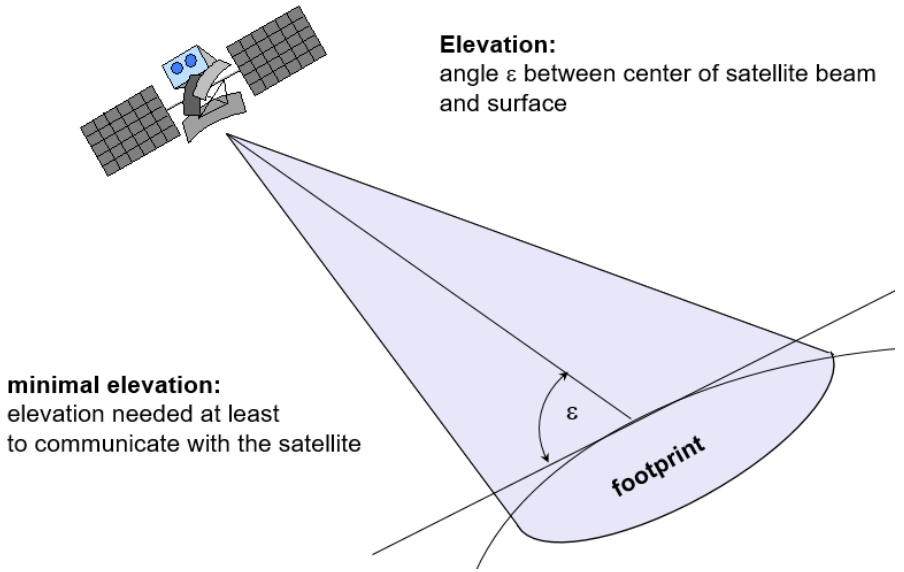




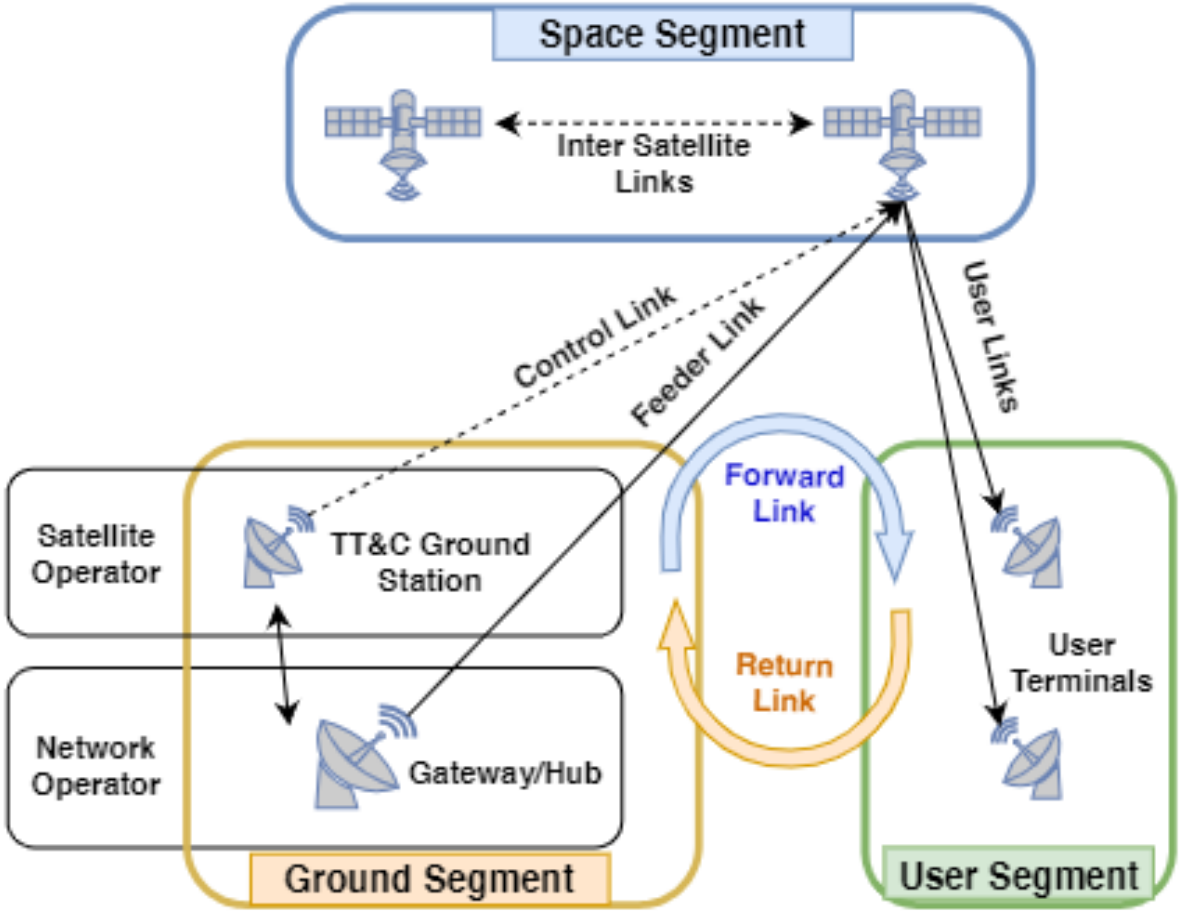


Inclination and elevation



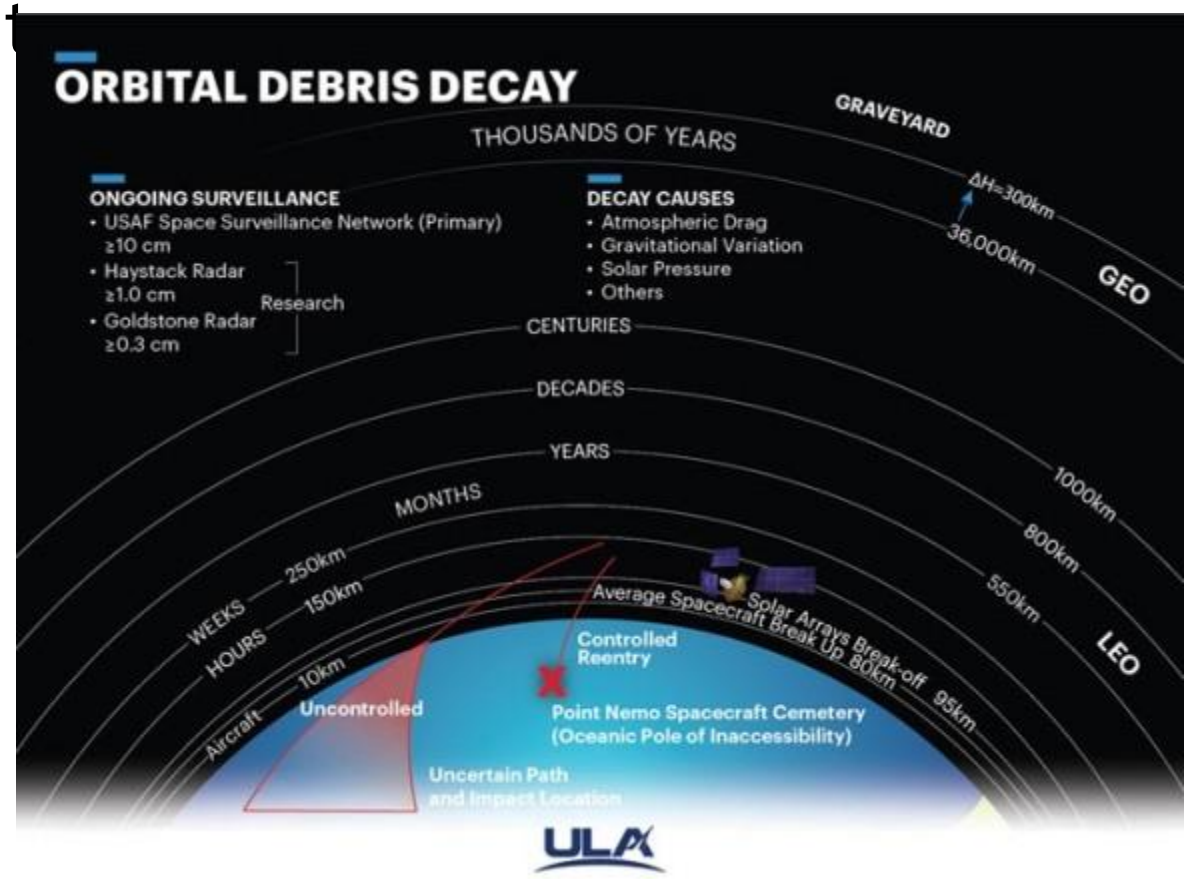


Satellite system elements



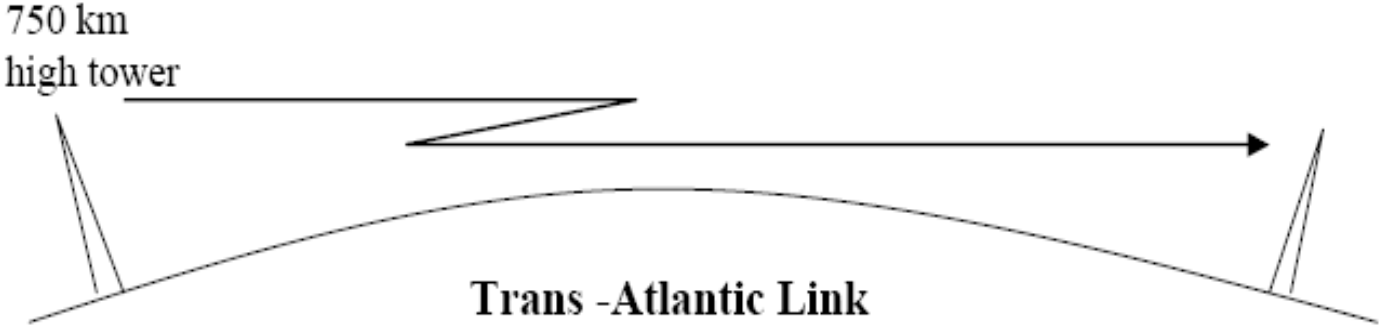
Space segment

- Satellite launch → Transfer orbit → Deployment → Operation → Retirement



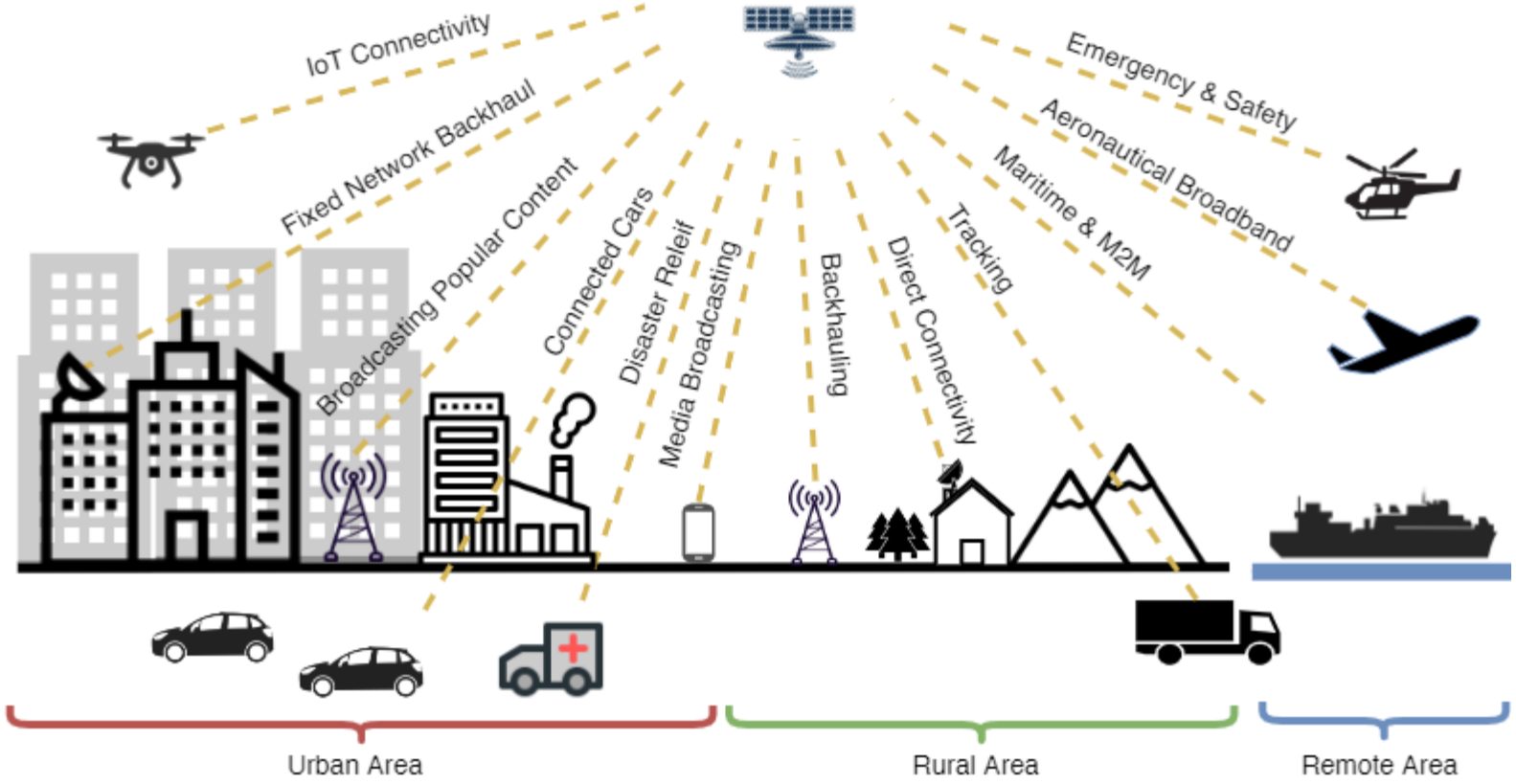
Communication satellite

- A large microwave repeater
- Contains several transponders
  - Listens to some portion of spectrum
  - Amplifies the incoming signal
  - Broadcasts it in another frequency to avoid interference with incoming signals (e.g. TV)
- Otherwise would require a surreally high tower for trans-atlantic wire



Use cases

- Of communication satellites



Satellite transmission bands

- C band is the most frequently used
- Ka and Ku bands are reserved exclusively for satellite
  attenuation

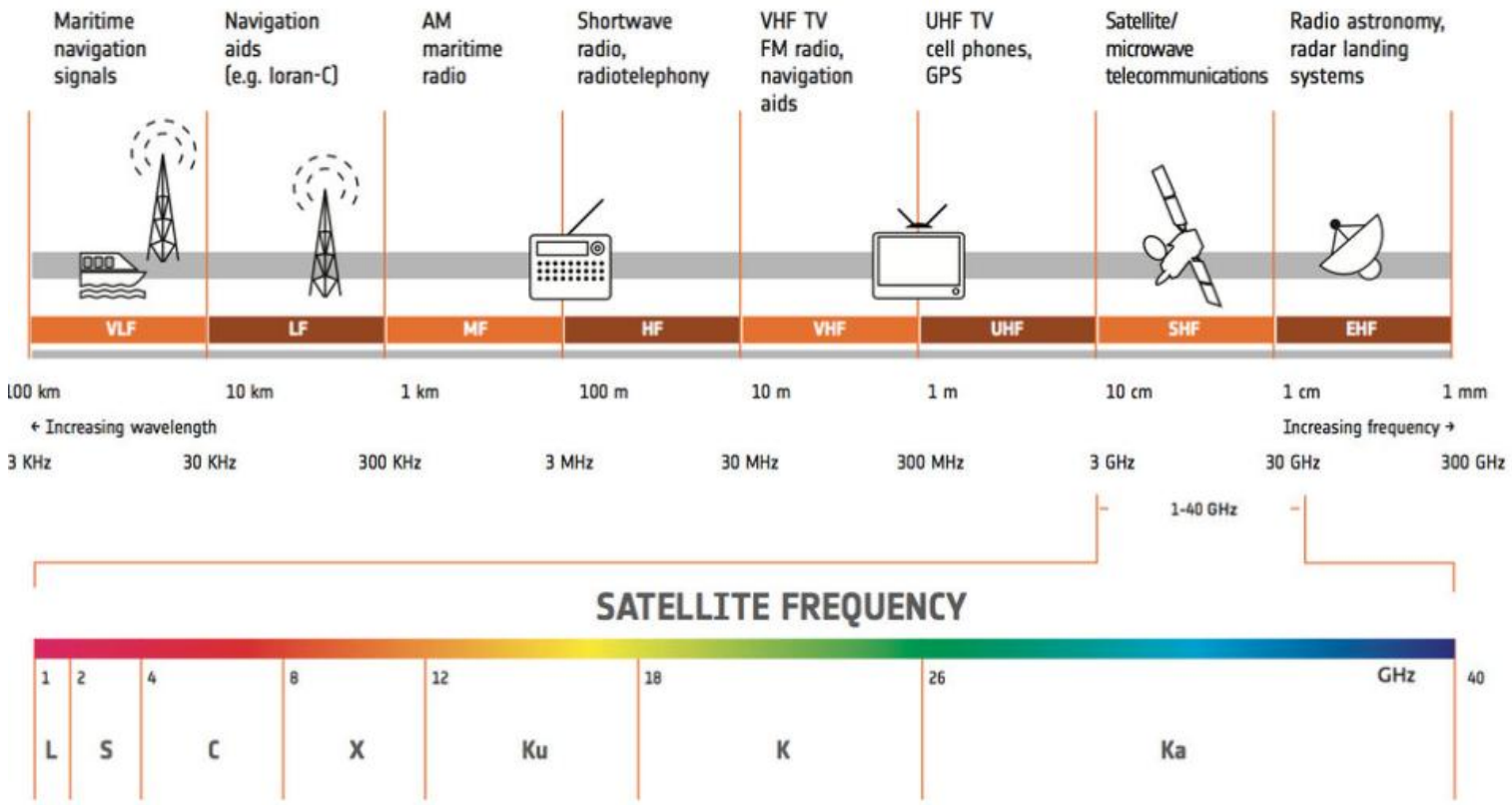


Table 19 StarLink Frequency Allocation and Modulation Type

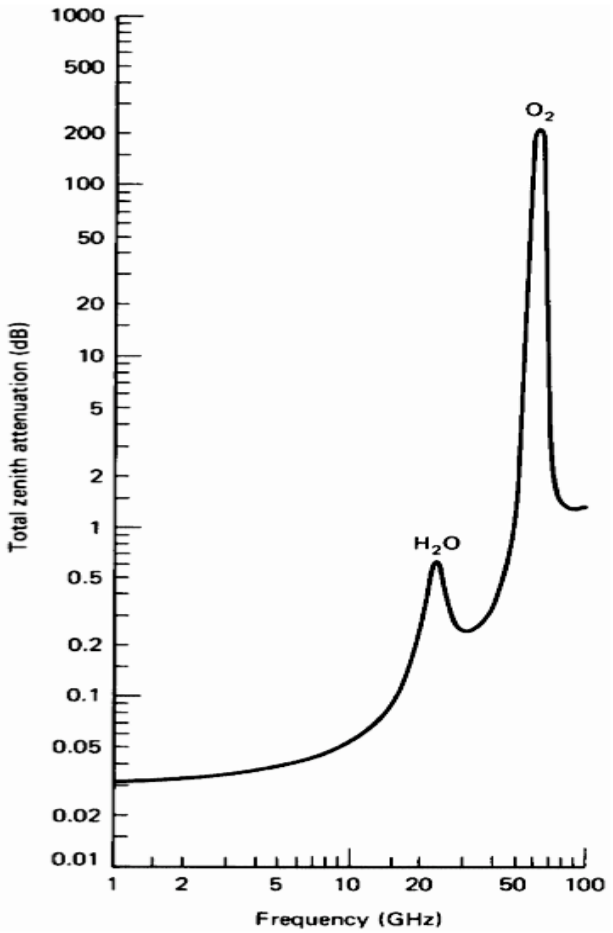
Characteristic	Uplink	Downlink
Frequency (GHz)	14.0 -14.5 27.5 - 29.1 29.5 - 30.0 47.2 - 52.4	10.7 - 12.7 17.8 - 18.6 18.8 - 19.3 37.5 - 42.5
Modulation Type	BPSK, QAM	OQPSK, QAM

Attenuation

- Different types of atmospheric losses can disturb radio wave transmission in satellite systems
  - Atmospheric absorption
  - Atmospheric attenuation
  - Traveling ionospheric disturbances

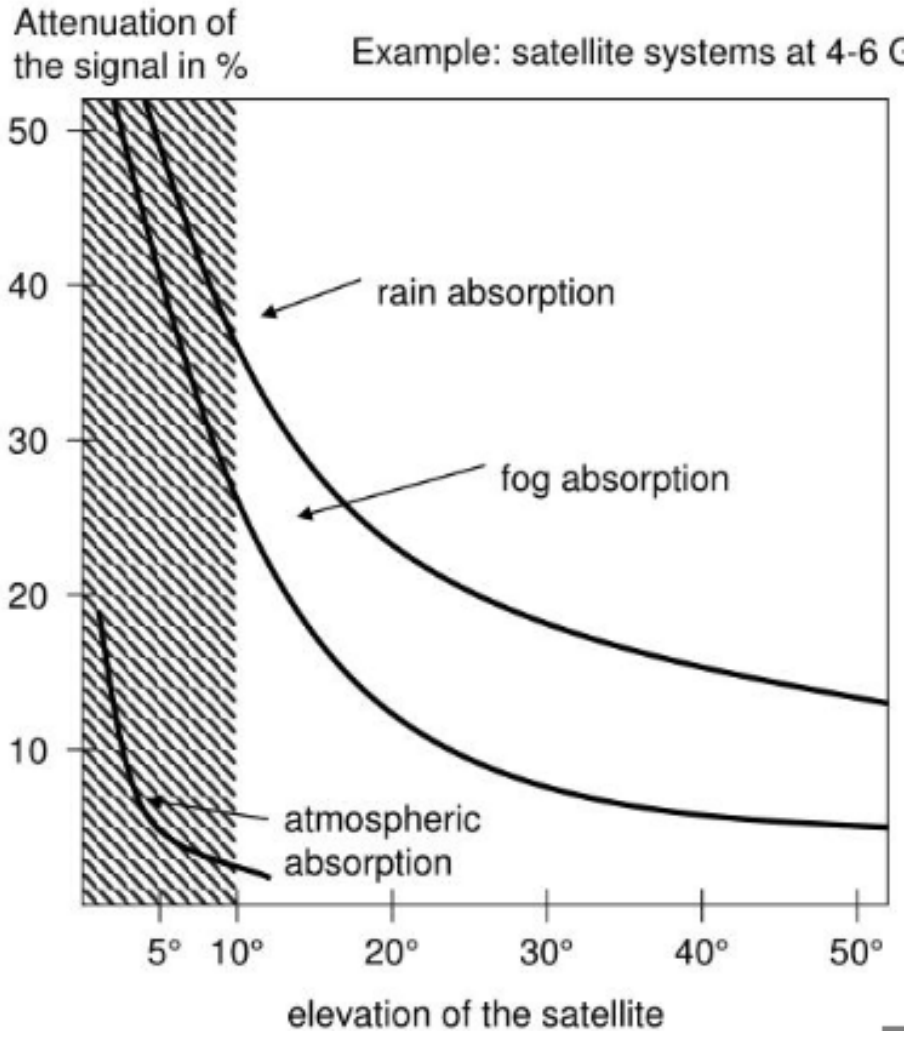
Atmospheric absorption

- Energy absorption by atmospheric gases, which varies with the frequency of the radio waves
- Two absorption peaks are observed (for 90º elevation angle):
  - 22.3 GHz from resonance absorption in water vapour (H_2O)
  - 60 GHz from resonance absorption in oxygen (O_2)



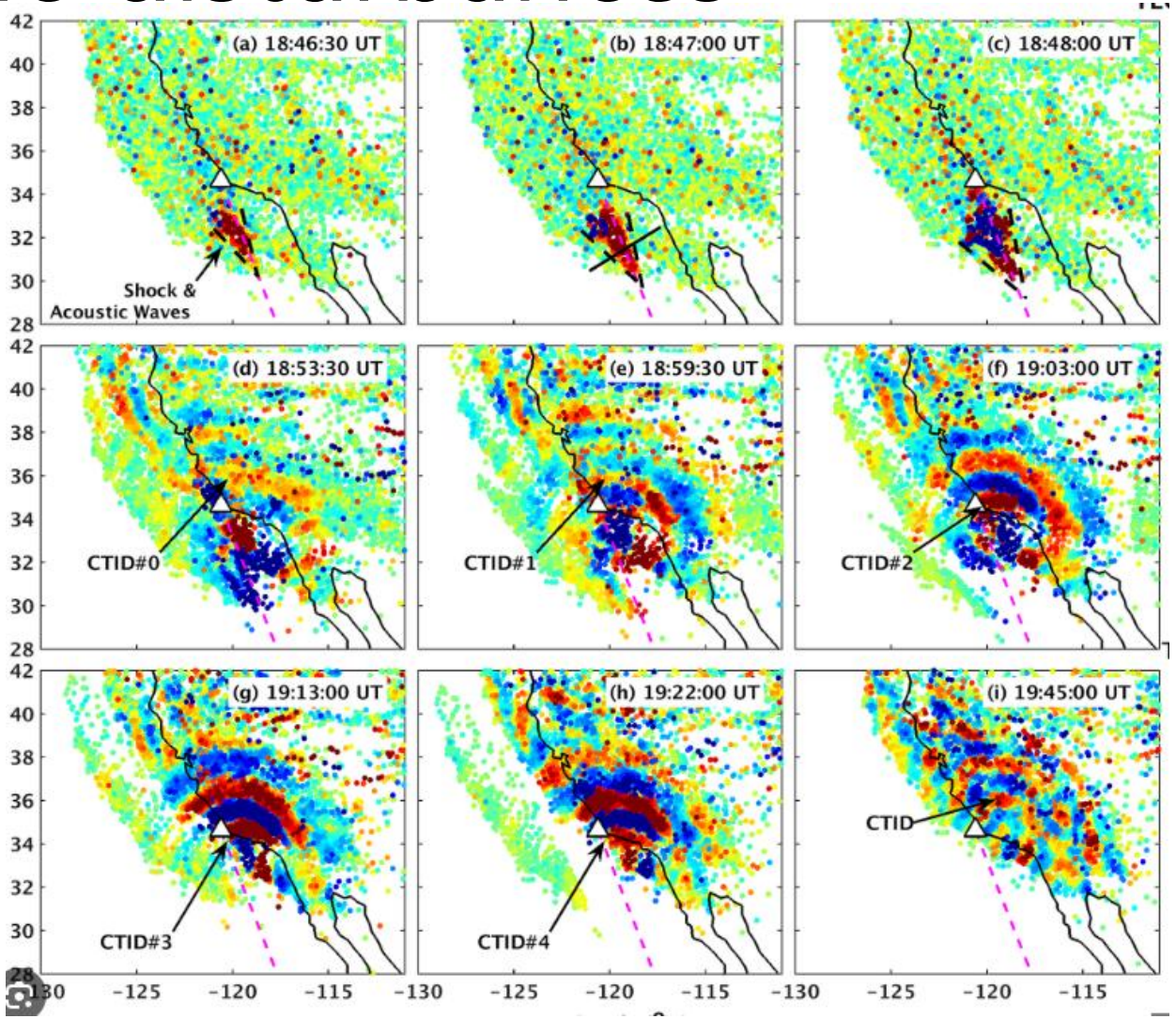
Atmospheric attenuation

- Rain is the main cause of atmospheric attenuation
  - Hail, ice and snow have little effect on attenuation because of their low water content
  - Total attenuation from rain can be determined by the effective path length of the signal through the rain



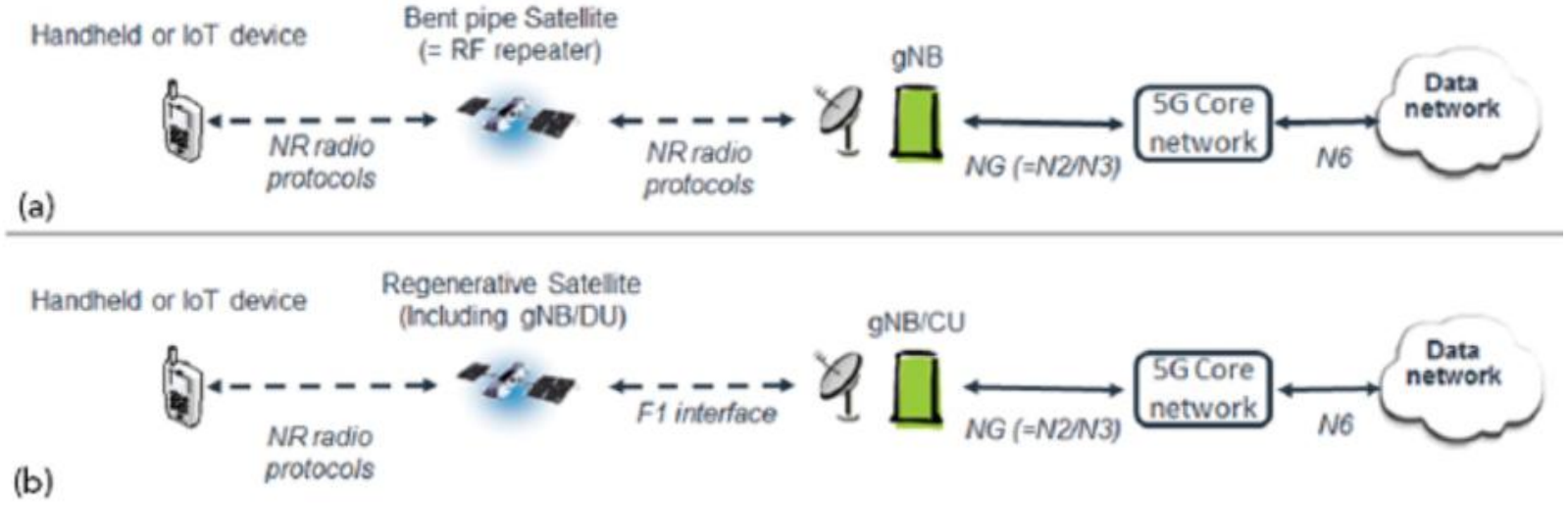
Traveling ionospheric disturbances

- Traveling ionospheric disturbances are clouds of electrons in the ionosphere that provoke radio signal fluctuations which can only be determined on a statistical basis



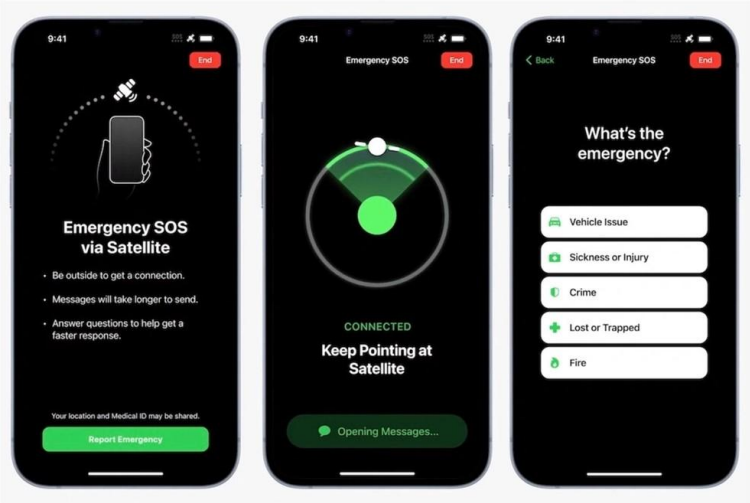
Current developments

- 480 Starlink satellites testing direct connectivity to smartphones next week
  - Texting in 2024 → Audio, video, and Internet in 2025
  - Threat to Internet and satellite TV industry for rural areas
- Base st



Current developments

- Apple +



- Starlink, St





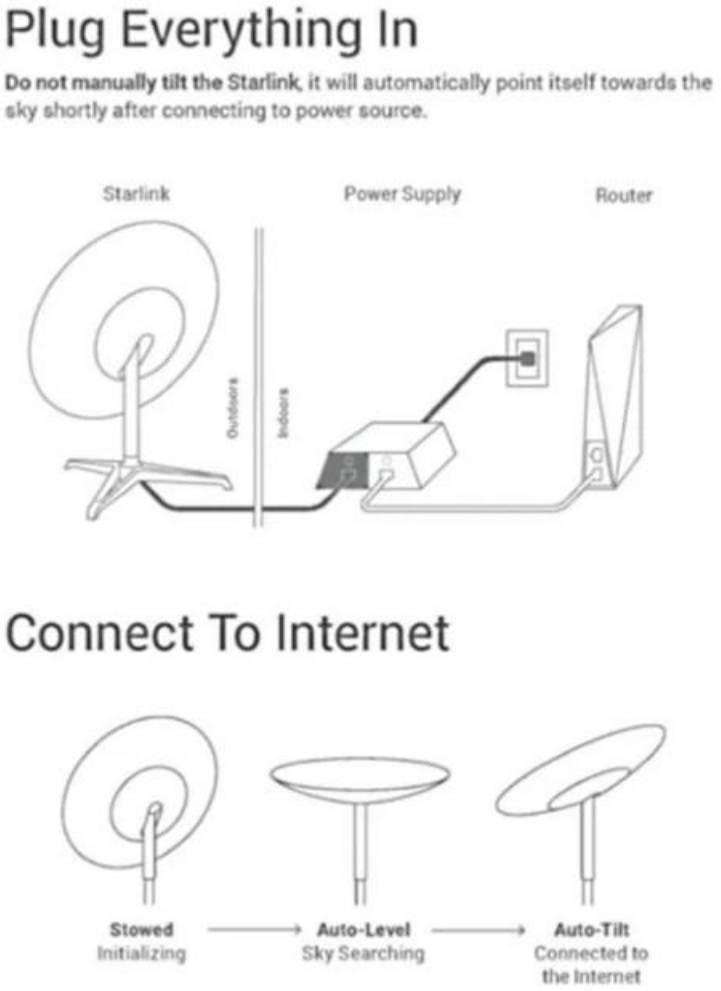
Starship prototypes serve as a backdrop for T-Mobile's Mike Sievert and SpaceX's Elon Musk. (T-Mobile Photo)

Current developments

- Starlink ante
- Ukraine

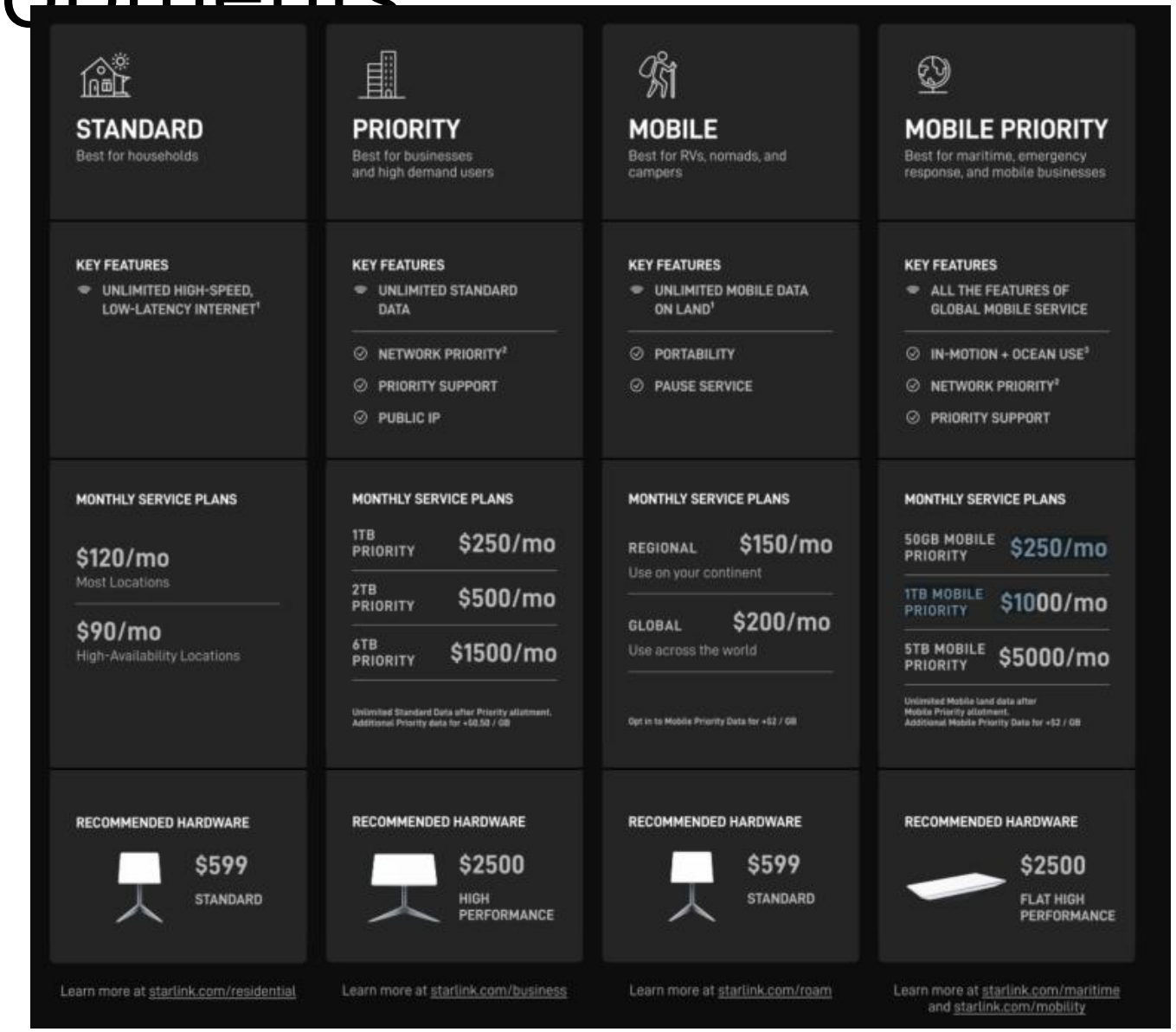




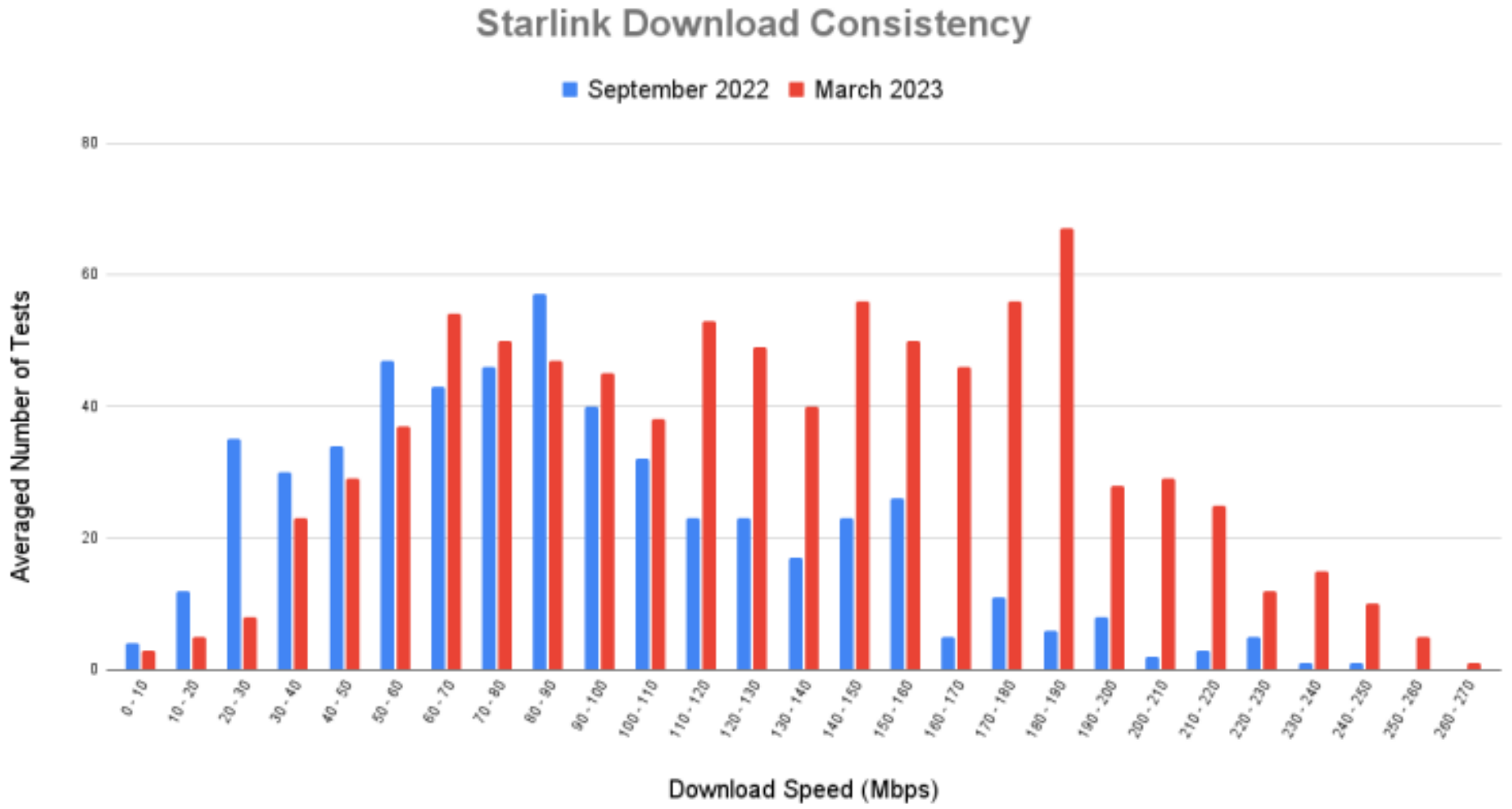


Current developments

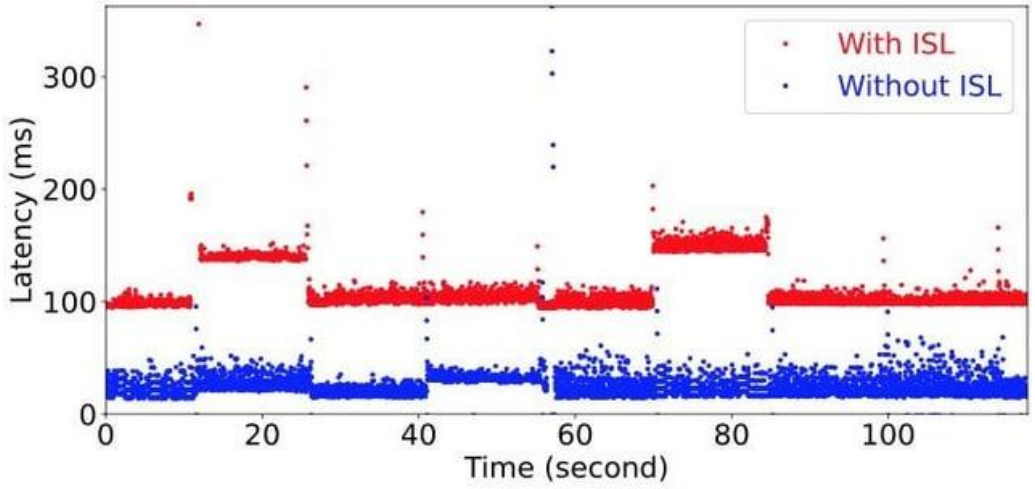
- Starlink plans



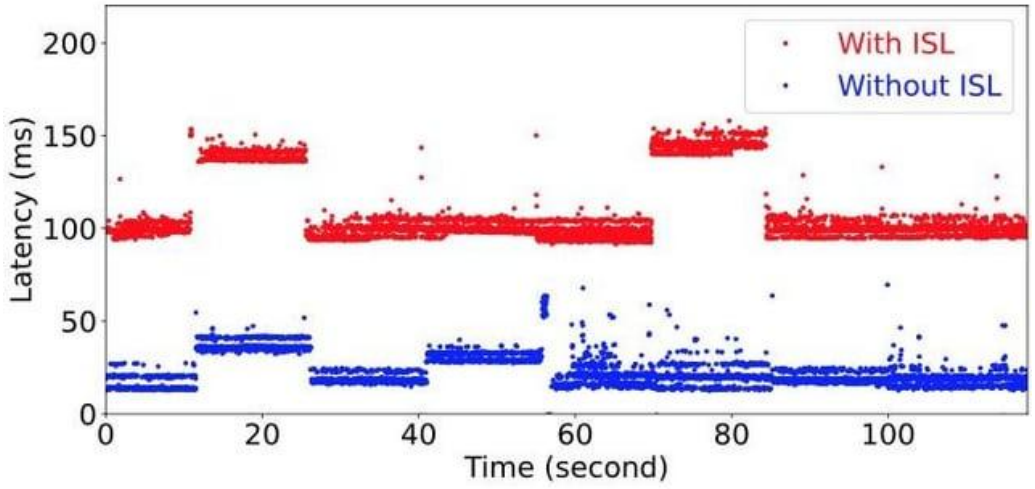
Current developments



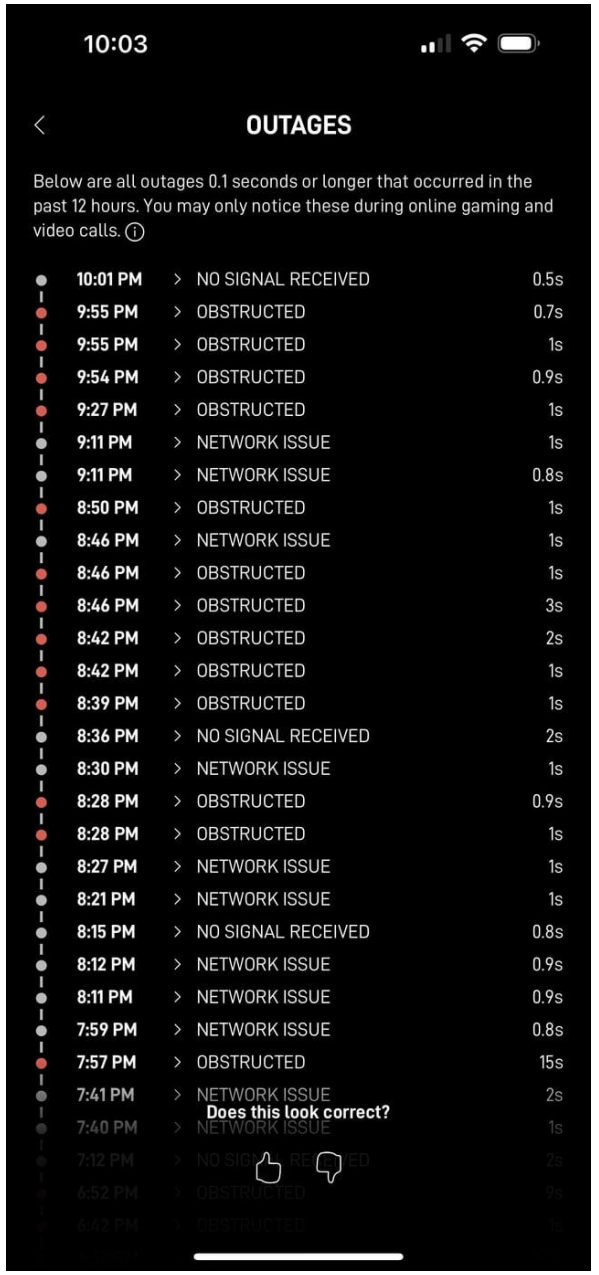
Current developments



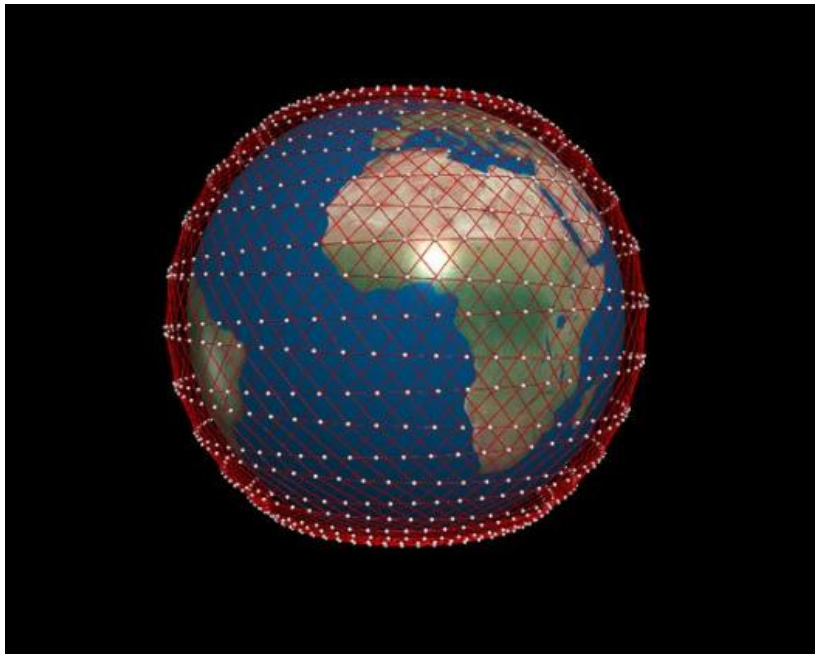
(a) Uplink OWD



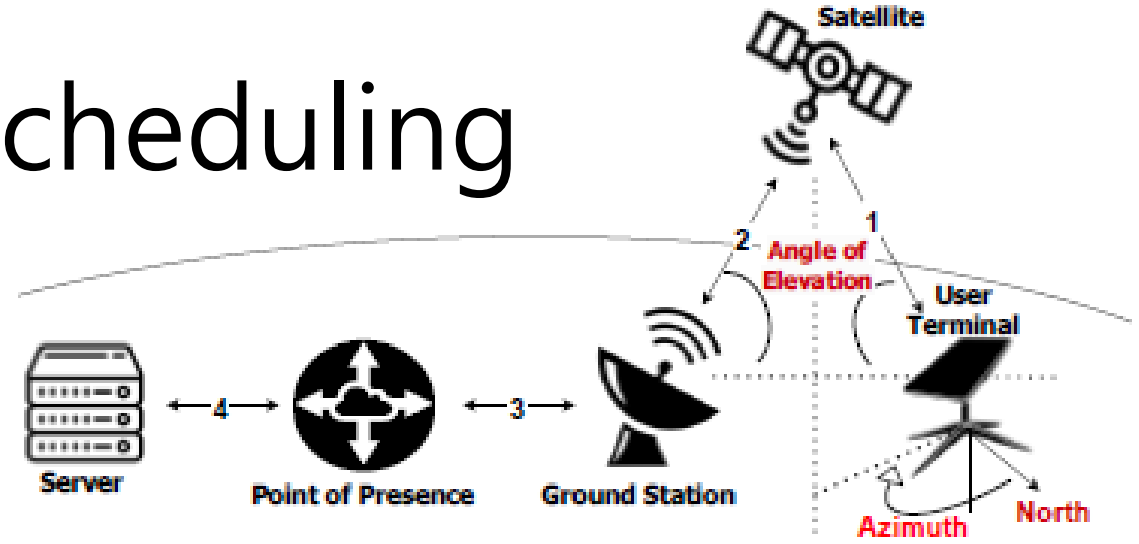
(b) Downlink OWD



Starlink Scheduling



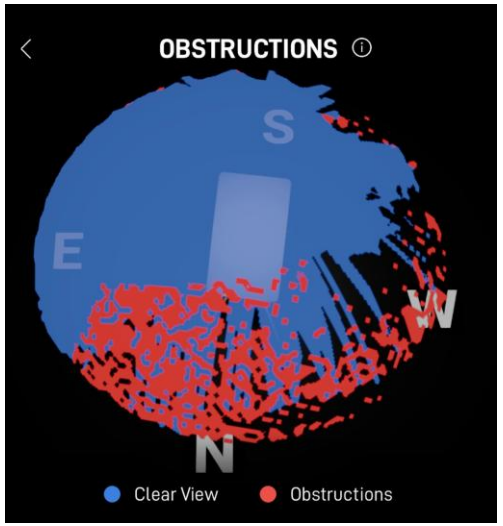
Starlink's hierarchical scheduling



- Two schedulers
  - Global network controller
  - MAC controller
- Global network controller
  - Allocates a satellite to each user terminal based on
    - Load, geospatial conditions, satellite charge, etc
  - Reschedules every 15 seconds, globally
- MAC controller schedules flows from the user terminals assigned to it
  - Round-robin

User terminals

- Phased-array antennas equipped with a motor
  - Motor physically repositions the angle of the dish to track fast moving satellites in the sky
    - Only used in initial calibration!
- Can connect to any satellite at AOE > 25°
- A terminal can connect to only one satellite at a time





Satellite

- Connects to multiple user terminals at a time
- Allocates radio frames to user terminals mapped to them to exchange data
  - On-board “MAC controller”
- MAC controller considers following factors when forwarding the traffic from user terminals to ground stations
  - User priority
  - Current load
  - Per-terminal flow characteristics



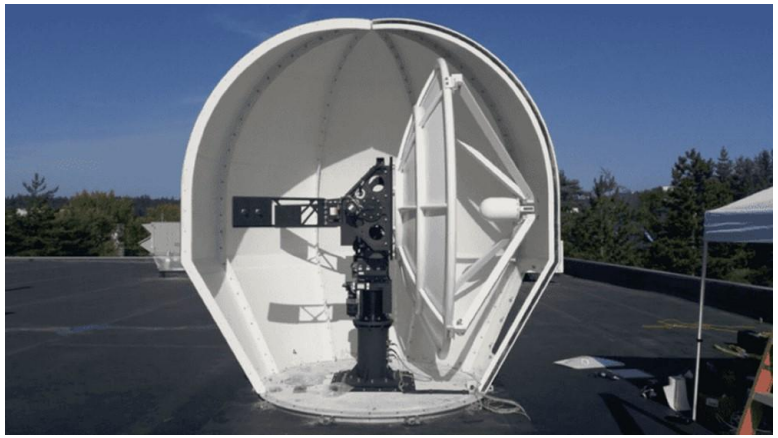






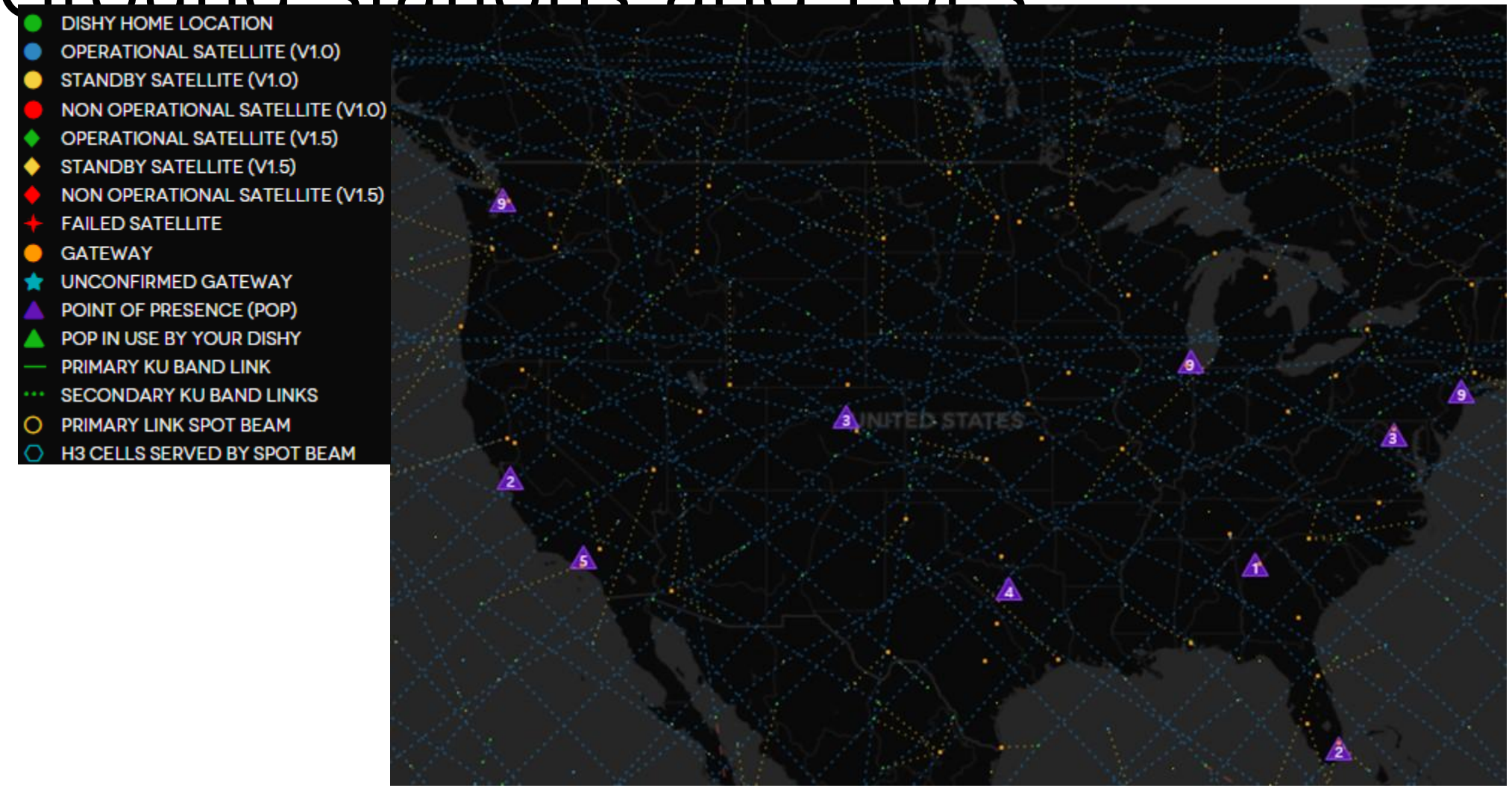
Ground stations and PoPs

- Ground stations consist of a set of phased-array antennas
  - Receive traffic from satellites and send it through wired links to Starlink's PoPs
  - Can communicate with satellites at AOE > 25◦
- PoPs are connected to the Internet backbone
  - From the PoP, the traffic is routed to destination on the Internet

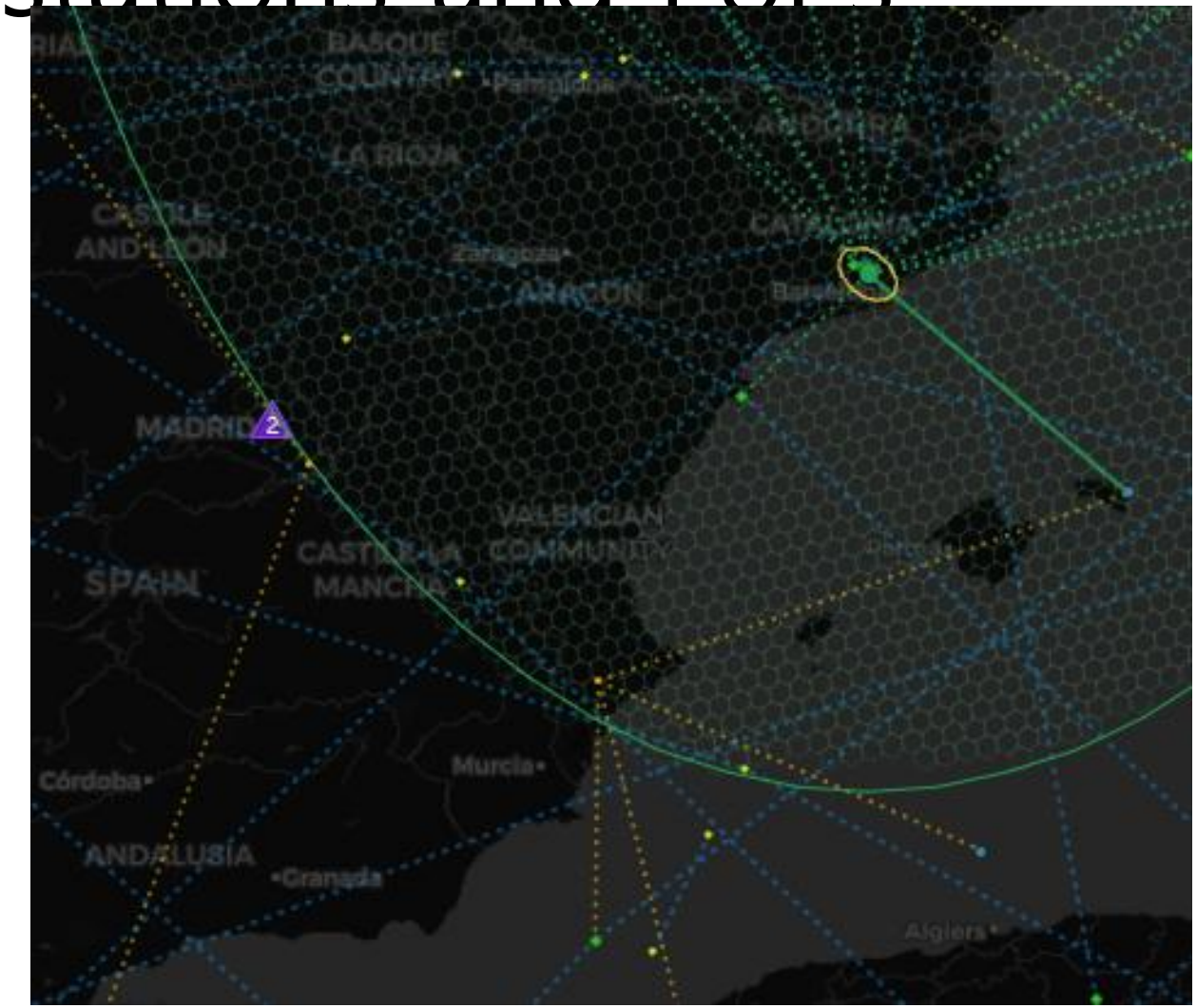




Ground stations and PoPs

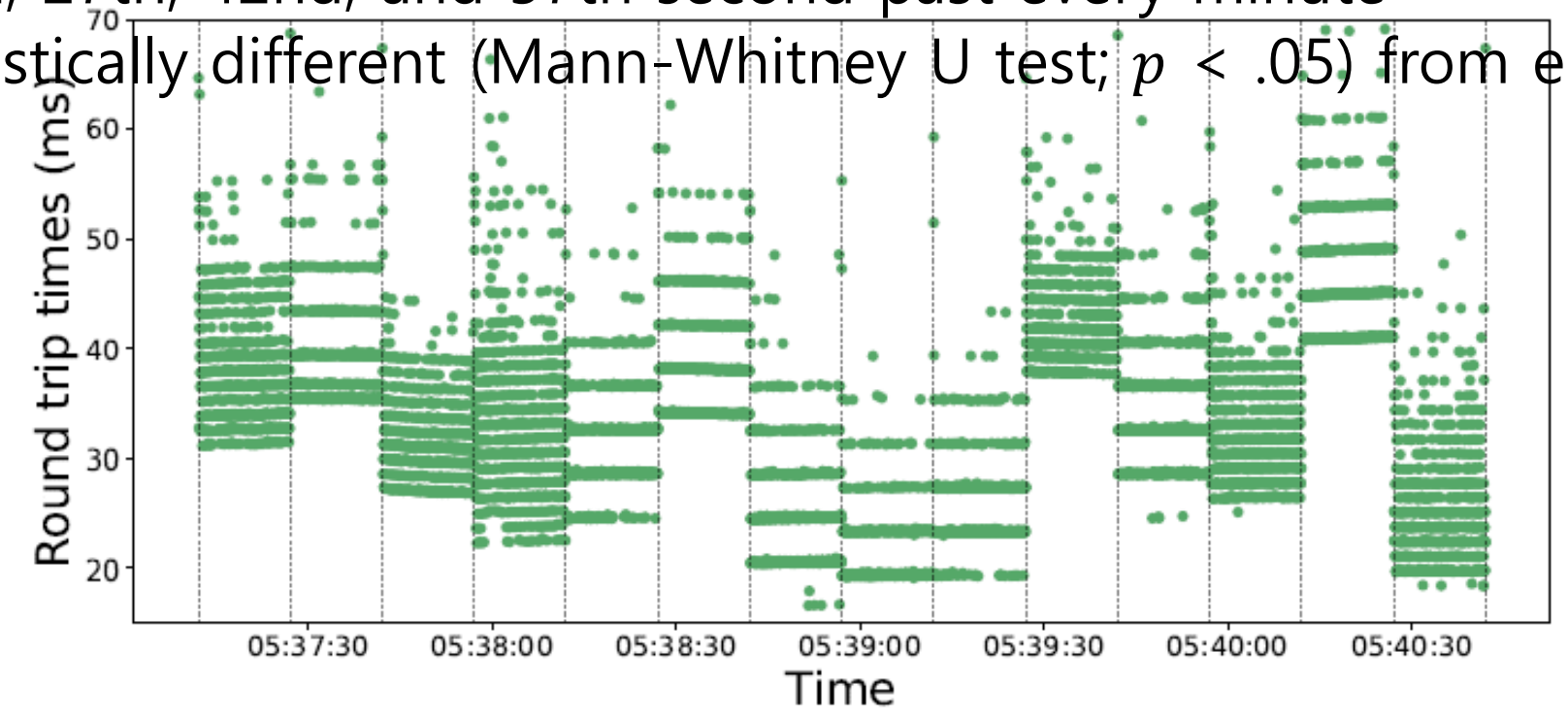


Ground stations and PoPs



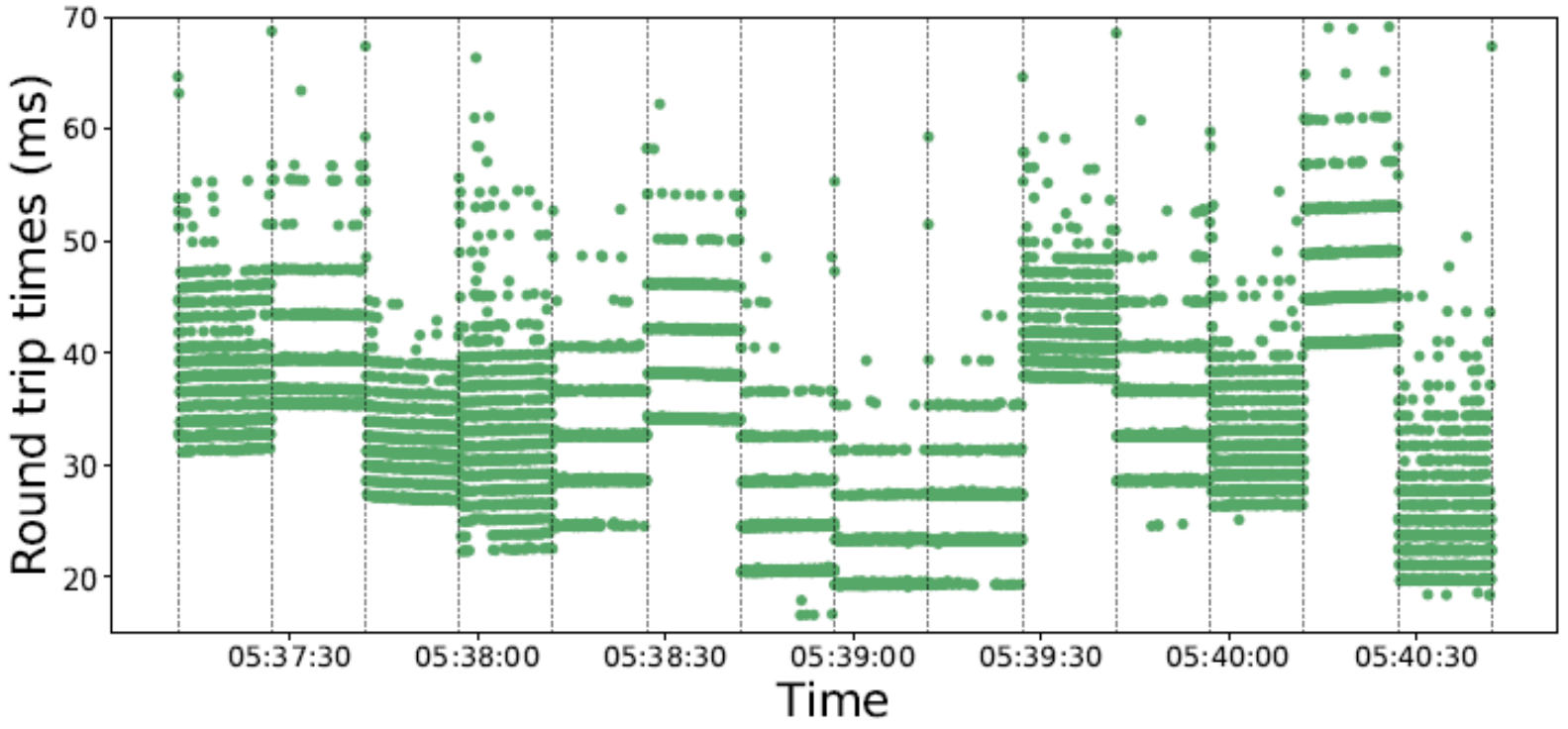
Manifestation in measured RTTs

- Ping @ 50 Hz
- Major changes in latency characteristics occur every 15 s
  - 12th, 27th, 42nd, and 57th second past every minute
  - Statistically different (Mann-Whitney U test; $p < .05$) from each other



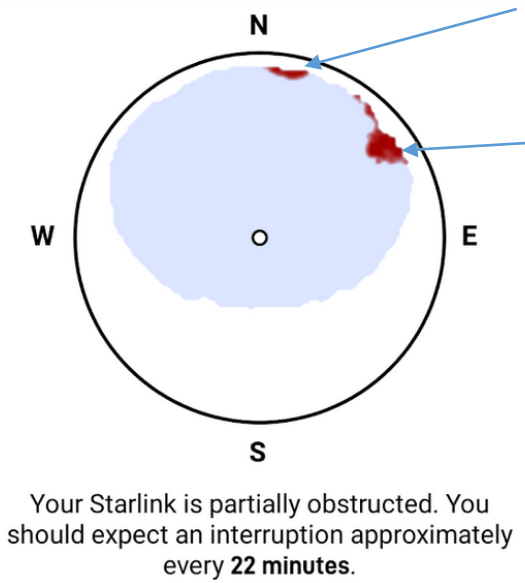
Manifestation in measured RTTs

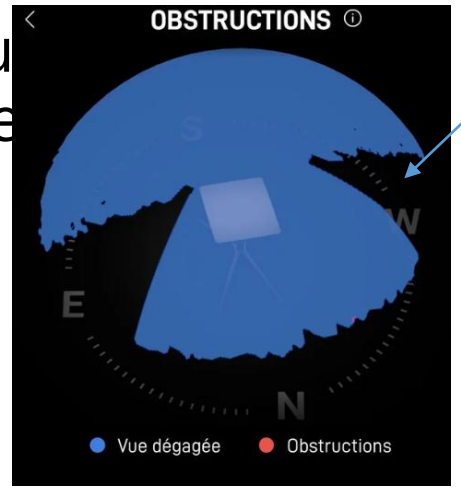
- Within the 15s time interval, latency frequently form parallel bands that are a few milliseconds apart
  - Radio frames are allocated to user terminals by an on-satellite contr



Obstruction maps

- 3d map
  - Created from 123px × 123px, 2-d images which mark the trajectory of satellites that recently served the user terminal
- Help users identify the quality of the location of their terminal
  - Physical obstru… their terminal and …t to serve the…





Firmware choosing not to Tx or Rx on either side of the equatorial band (a licensing requirement to prevent earth stations interfering with GEO satellites due to signal continuing on outward beyond LEO)

Global scheduler

- 35~44 satellites in the field of view of a user terminal in any 15 seconds slot
  - One of them will be selected for connection during a slot
- Median AOE of selected sats is 22.9° higher than others'
  - Only 30% are in 45~90° range
  - More energy-efficient
- Azimuths of selected sats skewed towards North
  - 82% of the time, while 58% of available sats are towards North

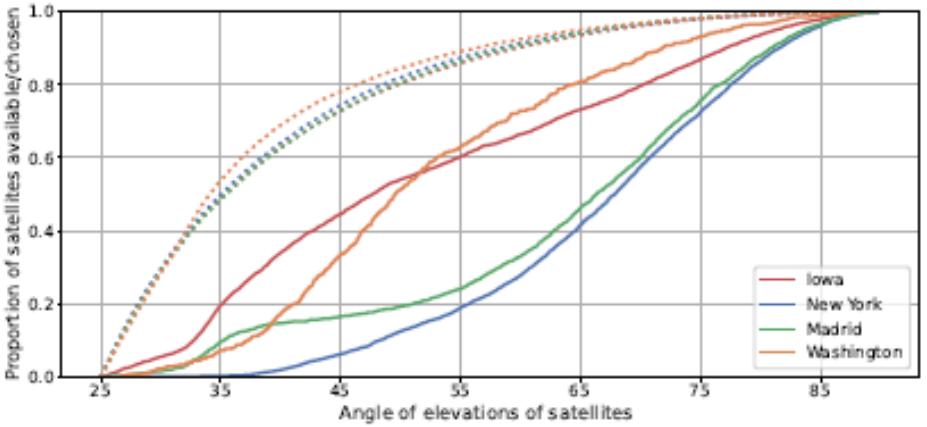


Figure 4: AOEs of available (dotted) vs. selected (solid) satellites.

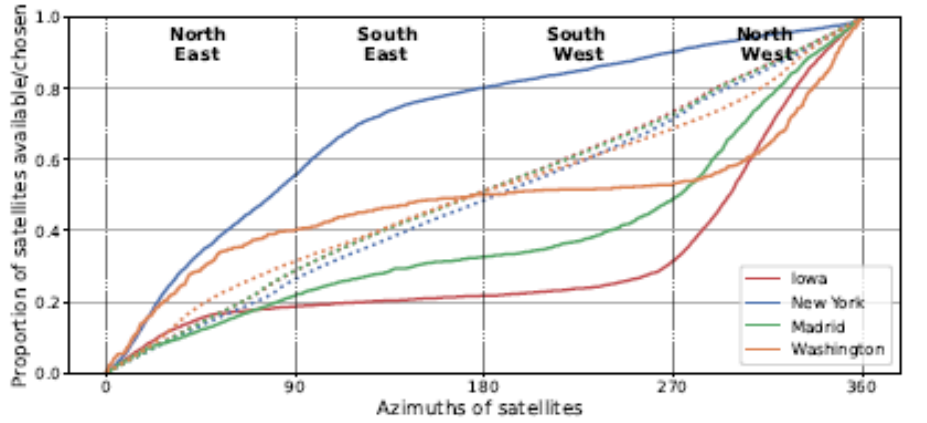
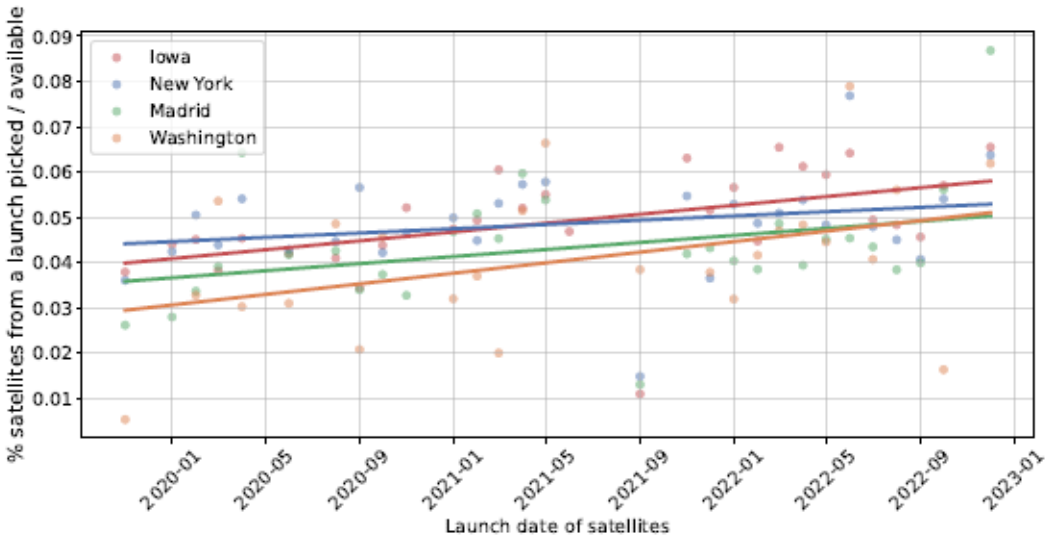


Figure 5: CDF of AZs of satellites available (dotted) vs. AZs of satellites chosen (solid). The x-axis is divided into 4 quadrants of

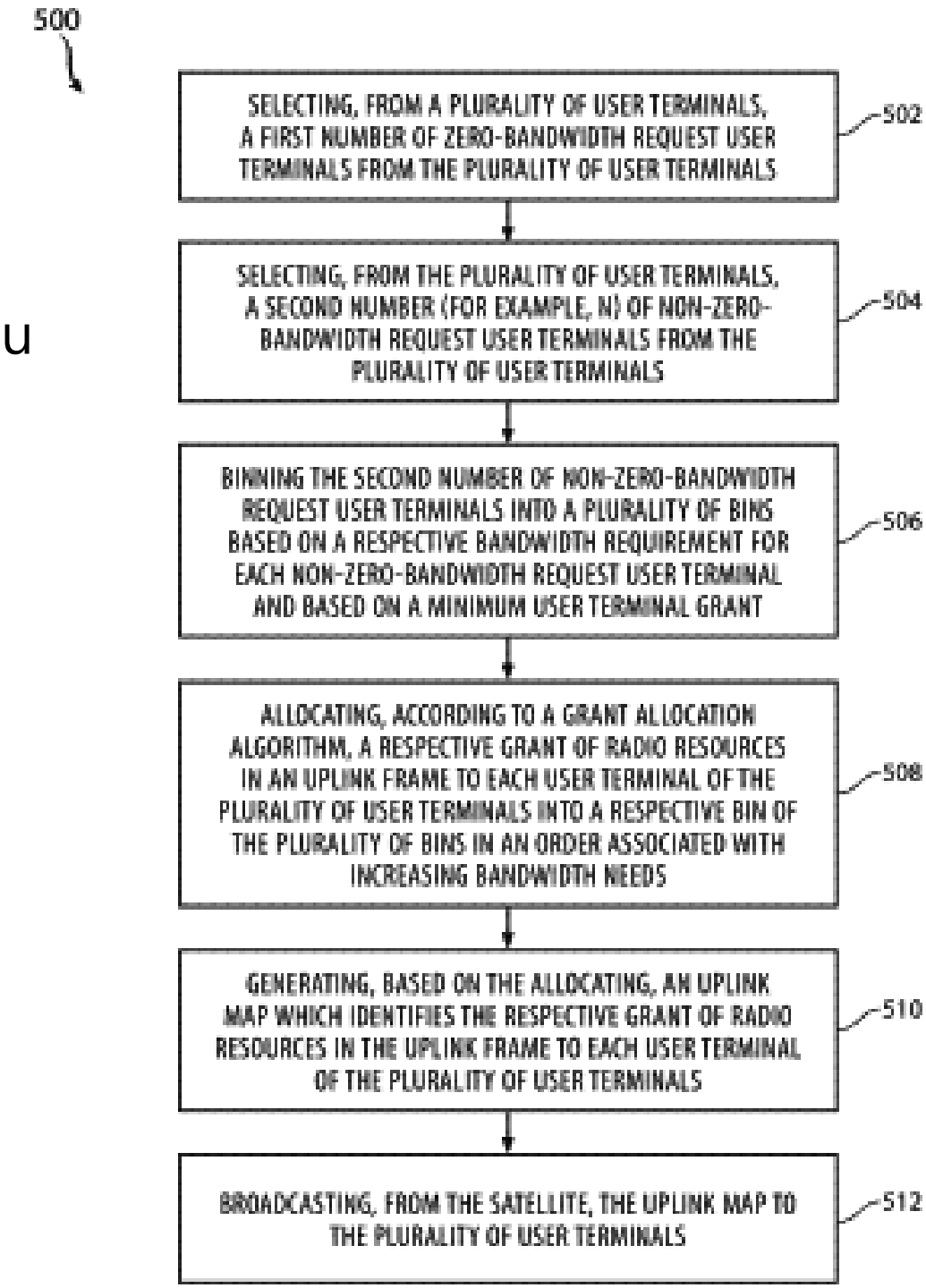
Global scheduler

- More likely to pick a satellite launched later
  - To evenly spread service times of satellites
  - Allowing the constellation to stay stable for longer
- More likely to pick a sunlit satellite
  - 72.3%
  - Dark satellites selected only when dark ones are over 35%
  - Selected dark sats 25° higher than sunlit counterparts



MAC scheduler

- US Patent 11,540,301 B1
  - System and method of providing a mediu access control scheduler
  - Issued Dec. 2022
  - Withdrawn? Not available in USPTO



Backup slides

Satellite positions

- Two Line Element (TLE) format
  - Location updated every 6 hours

Line 1	
Column	**Description**
01	Line Number of Element Data
03-07	Satellite Number
08	Classification (U=Unclassified)
10-11	International Designator (Last two digits of launch year)
12-14	International Designator (Launch number of the year)
15-17	International Designator (Piece of the launch)
19-20	Epoch Year (Last two digits of year)
21-32	Epoch (Day of the year and fractional portion of the day)
34-43	First Time Derivative of the Mean Motion
45-52	Second Time Derivative of Mean Motion (Leading decimal point assumed)
54-61	BSTAR drag term (Leading decimal point assumed)
63	Ephemeris type
65-68	Element number
69	Checksum (Modulo 10) (Letters, blanks, periods, plus signs = 0; minus signs = 1)

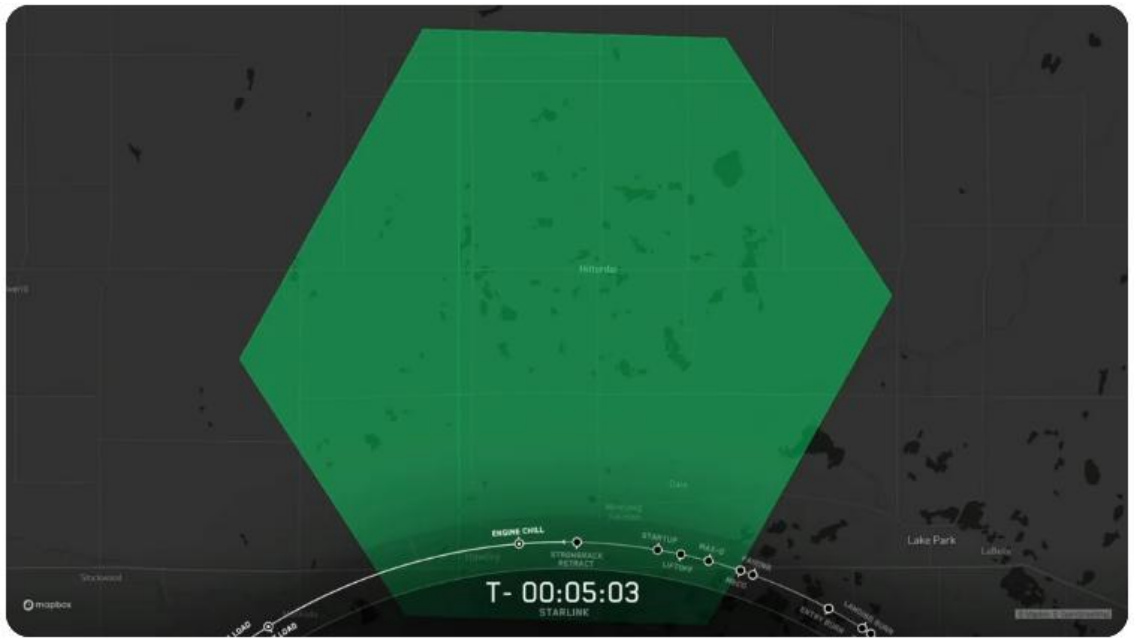
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NEXTSAT-2
1 56743U 23072A   23342.77527499  .00004997  00000+0  31737-3 0  9995
2 56743  97.5386 166.4202 0008377 355.1586   4.9561 15.09278777 29744
```

Line 2	
Column	**Description**
01	Line Number of Element Data
03-07	Satellite Number
09-16	Inclination [Degrees]
18-25	Right Ascension of the Ascending Node [Degrees]
27-33	Eccentricity (Leading decimal point assumed)
35-42	Argument of Perigee [Degrees]
44-51	Mean Anomaly [Degrees]
53-63	Mean Motion [Revs per day]
64-68	Revolution number at epoch [Revs]
69	Checksum (Modulo 10)

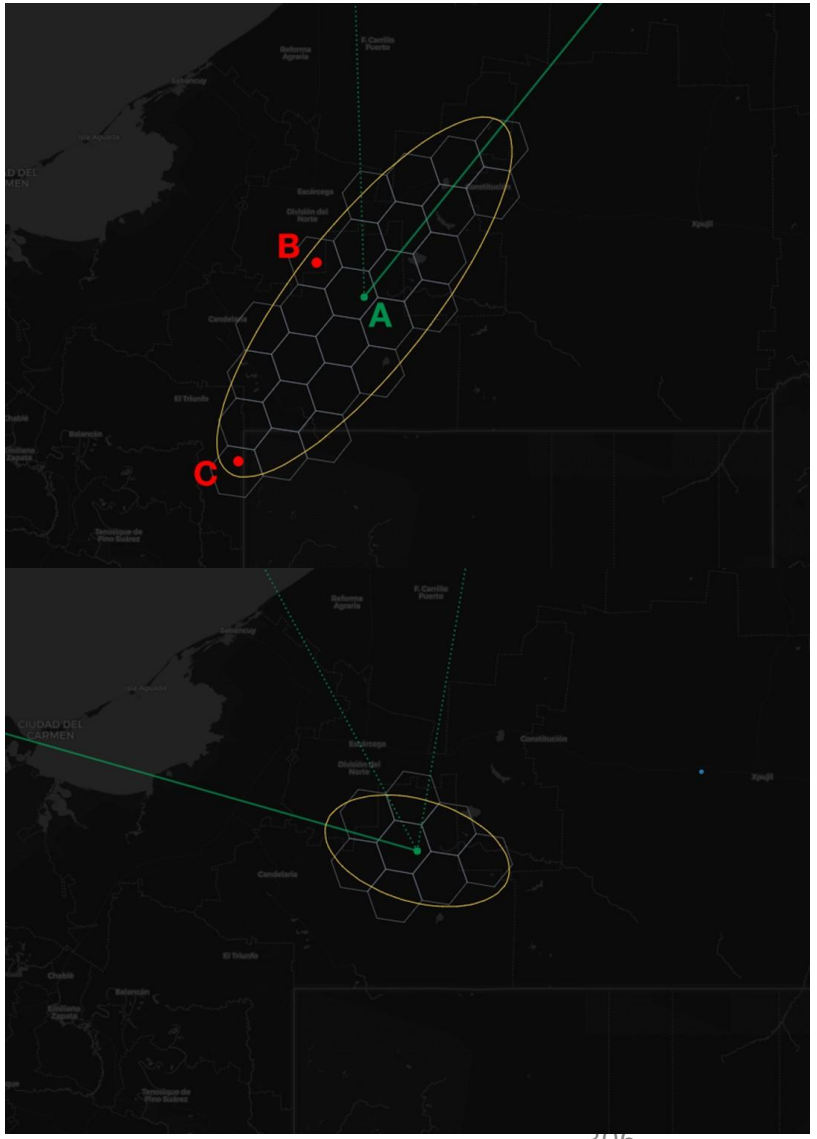
Starlink cells

- 24~25 km long diagonal
- Starlink “assigns a beam” to it, creating an “active cell”
  - Sats are programmed to target the cell as they fly by it



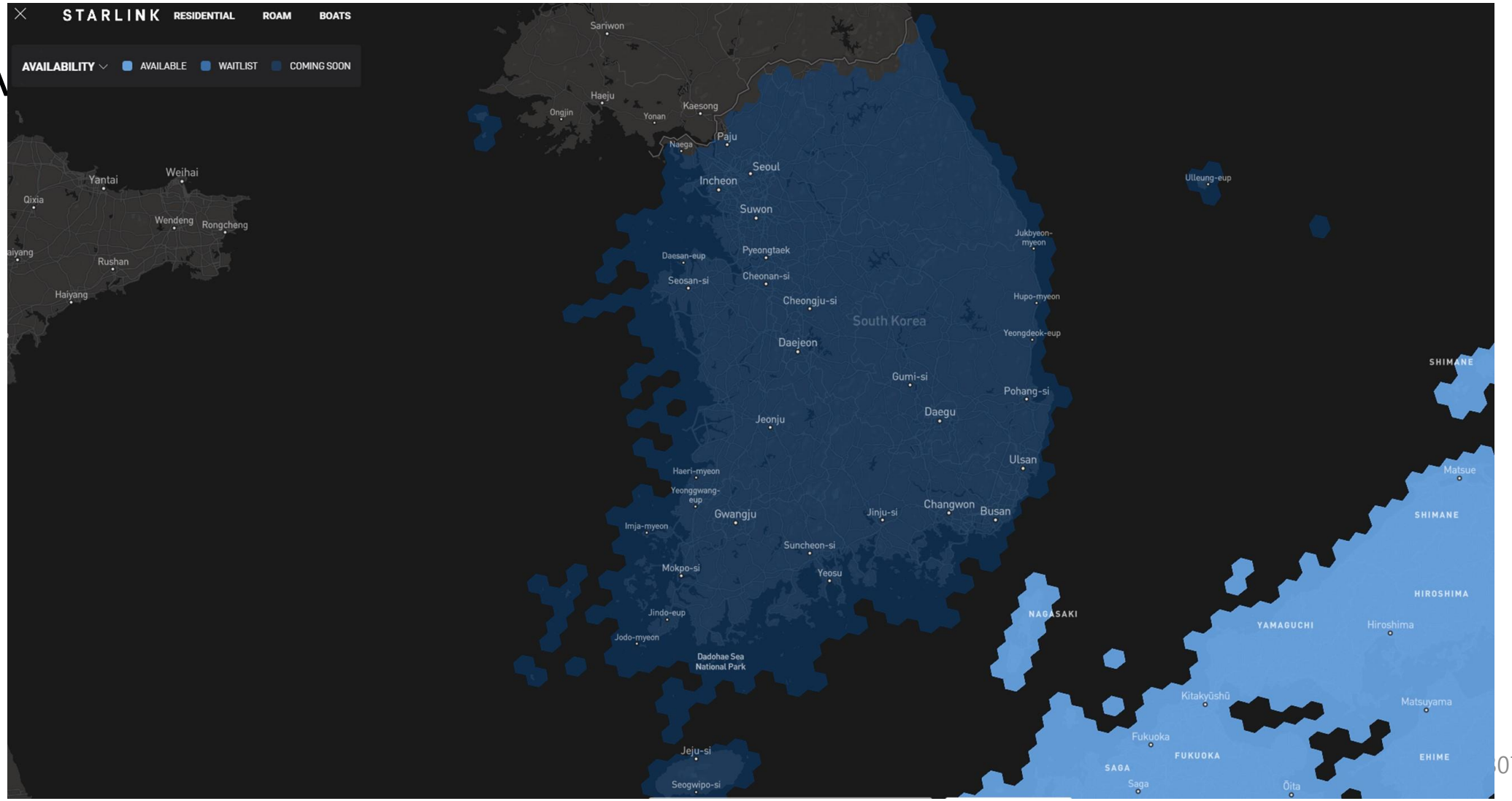
Starlink cells

- Cell A will get normal service, depending on local obstructions, etc.
- Cells B and C will also get service, but at lower SNRs
  - Any cell between A and C will also be able to get service
  - Any cells further away than B stand little chance of being served
- As the satellite moves, the ellipse rotates, and B will get service for a longer period of time than C



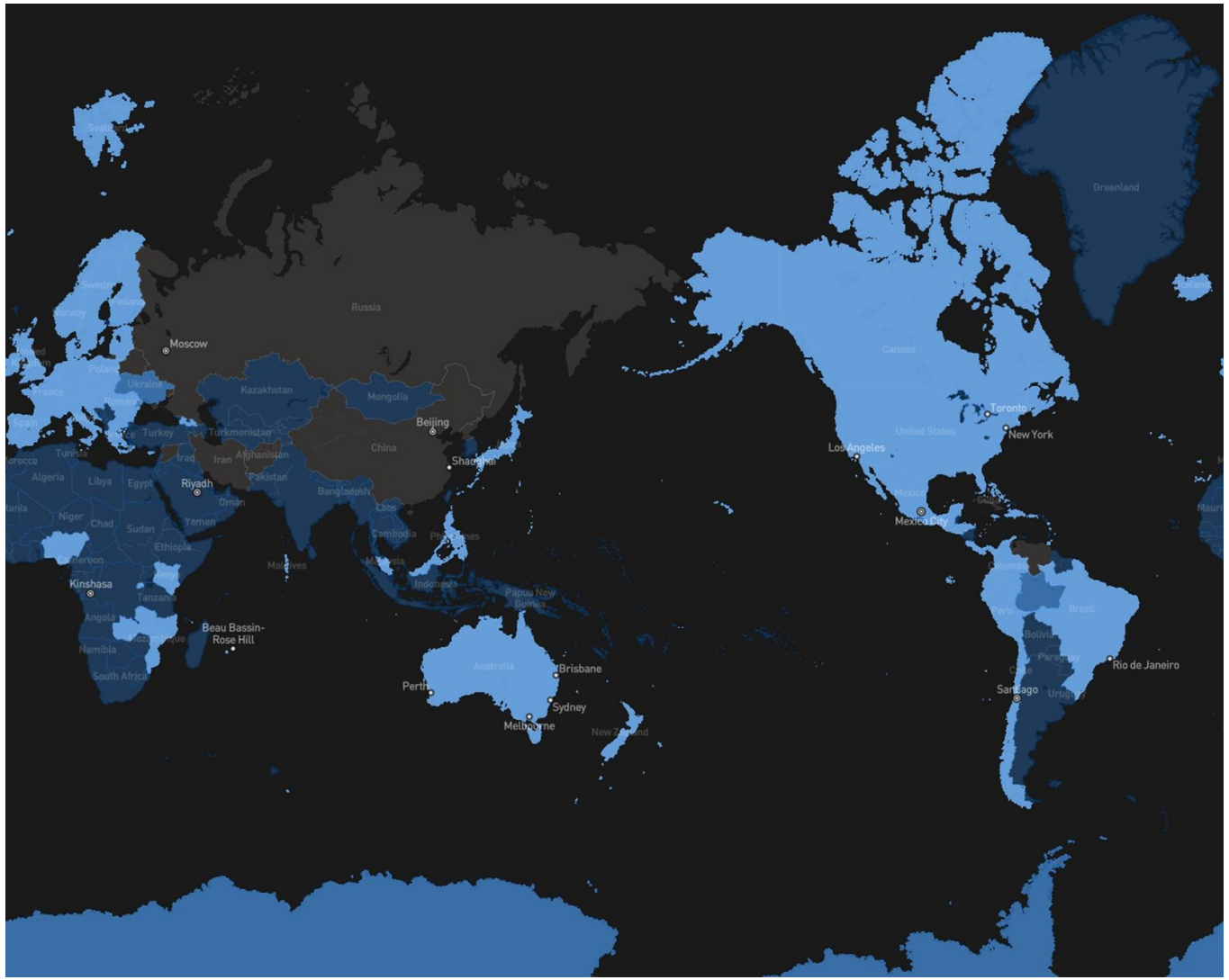
Starlink cells

- A



Starlink cells

- As of Dec.



Starlink cells

- Active vs. inactive cells would depend on s sity and t

