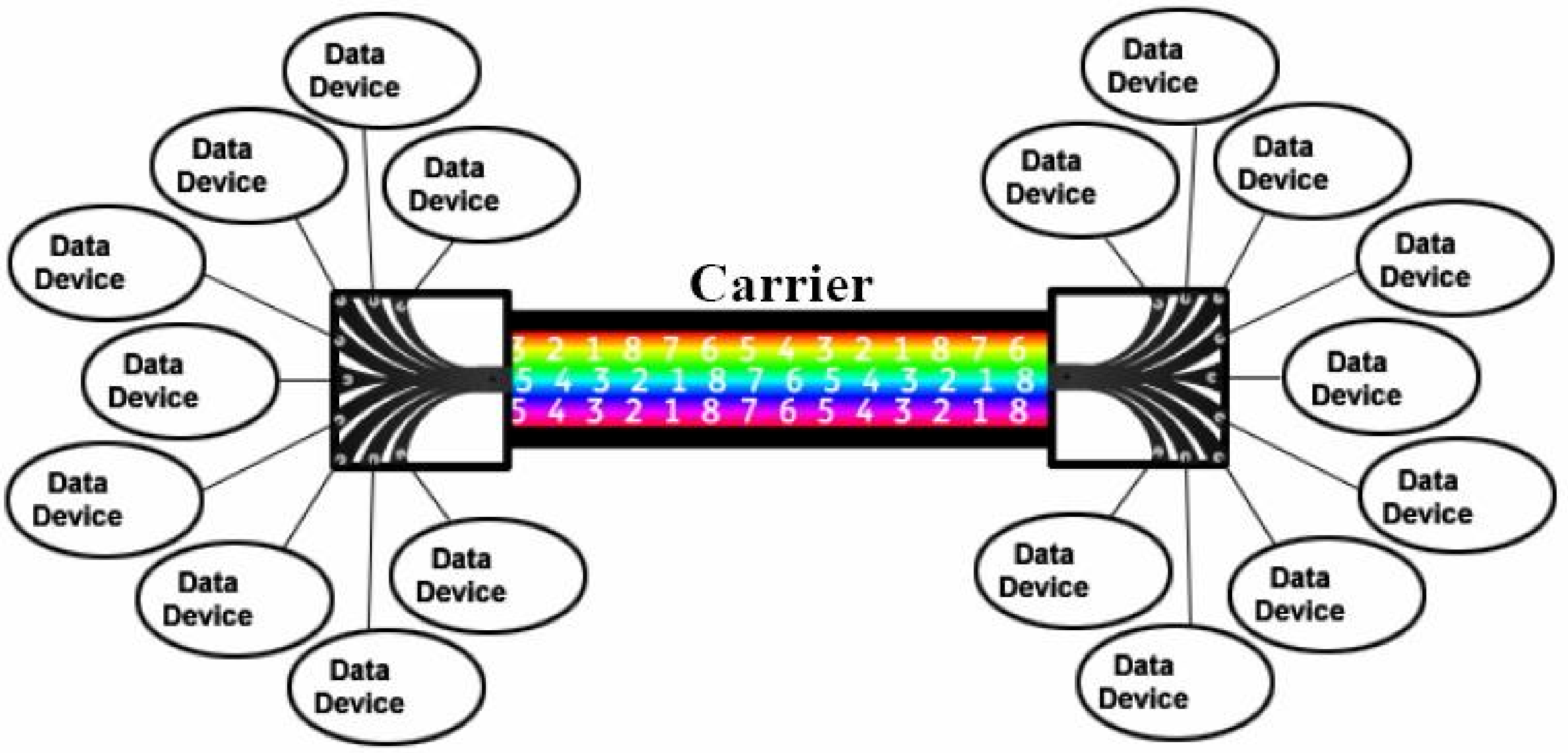
Computer Networks and Internets

Multiplexing
and
Demultiplexing
(Channelization)



Topics Covered

- Introduction
- The Concept of Multiplexing
- The Basic Types of Multiplexing
- Frequency Division Multiplexing (FDM)
- Using a Range of Frequencies Per Channel
- Hierarchical FDM
- Wavelength Division Multiplexing (WDM)
- Time Division Multiplexing (TDM)

  Synchronous TDM
- Framing Used in the Telephone System Version of TDM
- Hierarchical TDM
- The Problem with Synchronous TDM: Unfilled Slots
- Statistical TDM
- Inverse Multiplexing
- Code Division Multiplexing

Introduction

- This chapter
  - continues the discussion of data communications by introducing multiplexing
  - describes the motivation
  - defines basic types of multiplexing that are used throughout computer networks and the Internet
  - explains how modulated carriers provide the basis for many multiplexing mechanisms

The Concept of Multiplexing

- Multiplexing to refer to the combination of information streams from multiple sources for transmission over a ***shared medium***
  - Multiplexor is a mechanism that implements the concept
- Demultiplexing to refer to the separation of a combination back into separate information streams
  - Demultiplexor to refer to a mechanism that implements the concept
- Figure 11.1 illustrates the concept
  - each sender communicates with a single receiver
  - all pairs share a single transmission medium
  - multiplexor combines information from the senders for transmission in such a way that the demultiplexor can separate the information for receivers

The Concept of Multiplexing

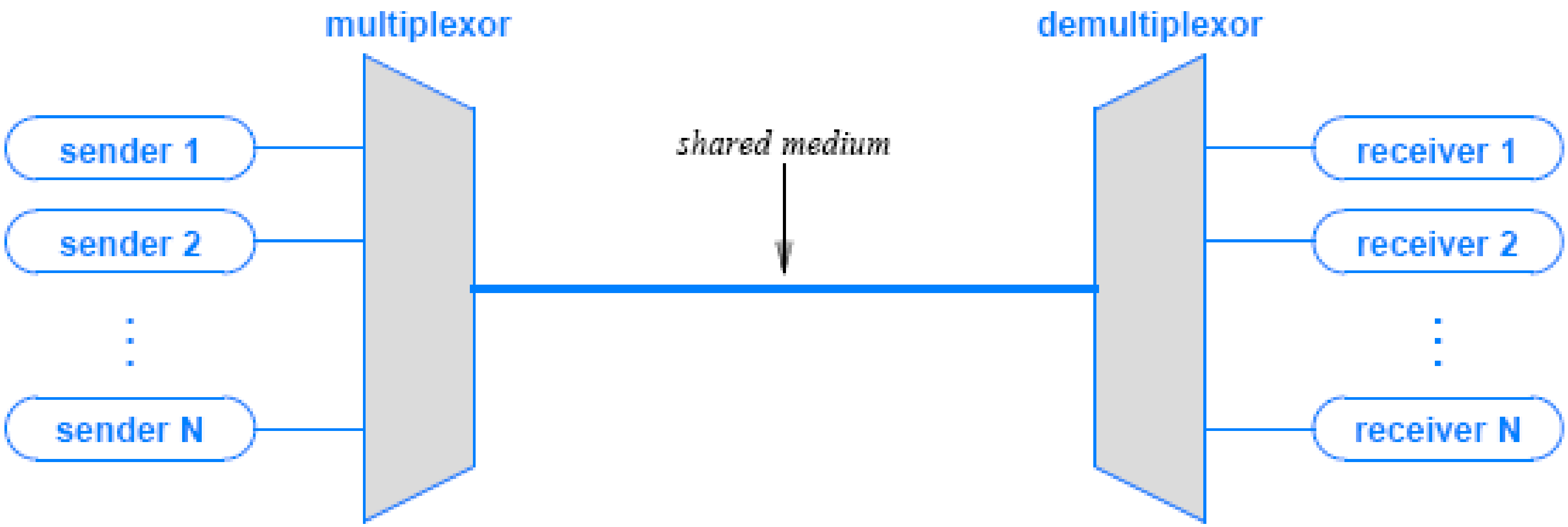
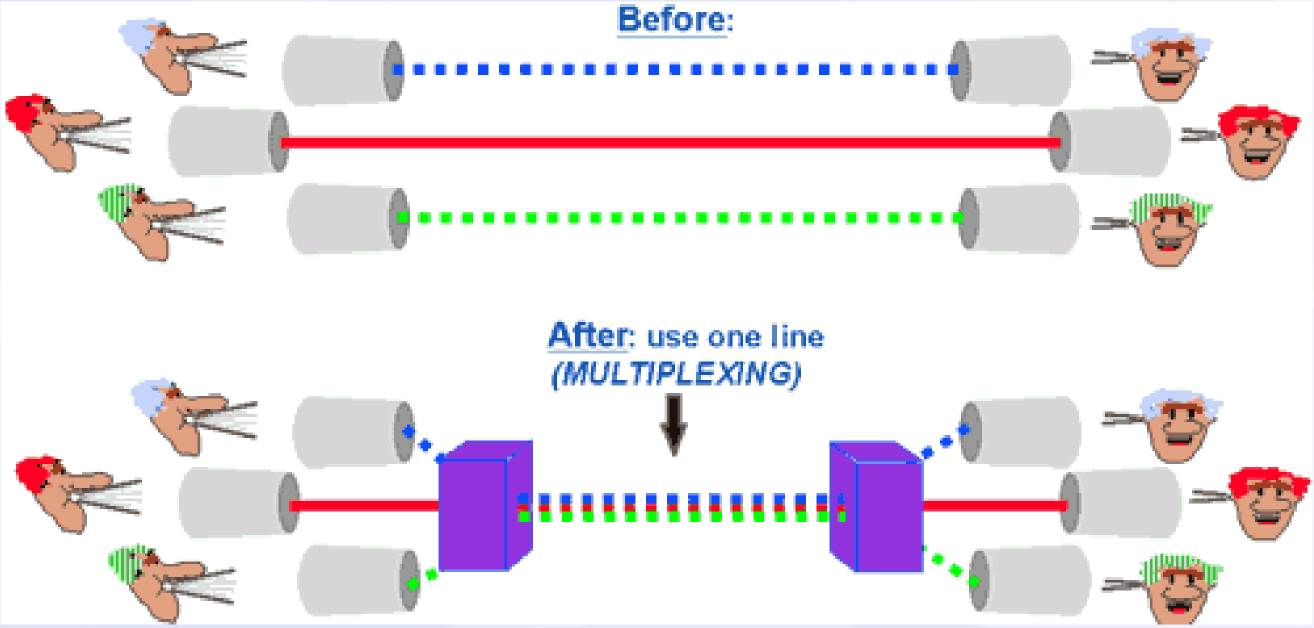
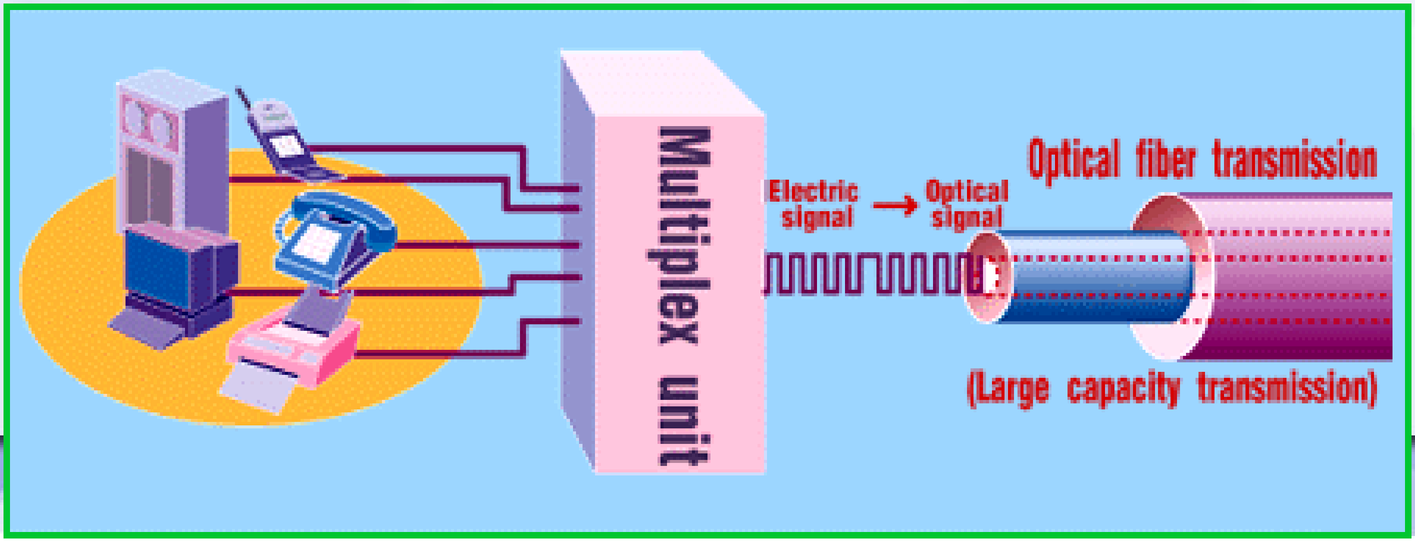


Figure 11.1 The concept of multiplexing in which independent pairs of senders and receivers share a transmission medium.

Multiplexing in networks

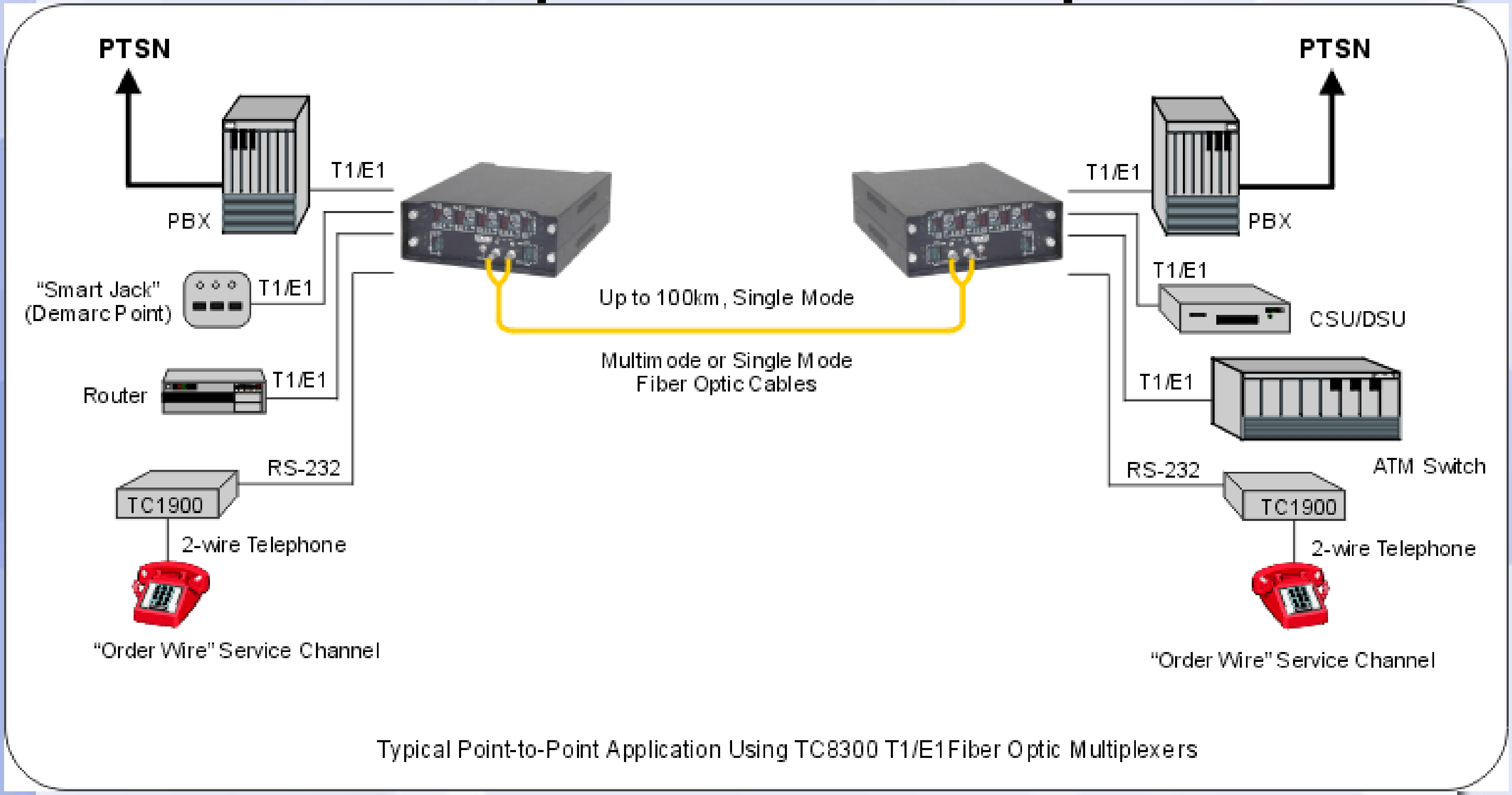




Main purpose is ?

Sharing the medium

Multiplexer example



Typical Point-to-Point Application Using TC8300 T1/E1 Fiber Optic Multiplexers

The Basic Types of Multiplexing

- There are four basic approaches to multiplexing that each have a set of variations and implementations
  - Frequency Division Multiplexing (FDM)
  - Wavelength Division Multiplexing (WDM)
  - Time Division Multiplexing (TDM)
  - Code Division Multiplexing (CDM)
- TDM and FDM are widely used
- WDM is a form of FDM used for optical fiber
- CDM is a mathematical approach used in cell phone mechanisms

Frequency Division Multiplexing

- A set of radio stations/TV can transmit electromagnetic signals simultaneously
  - With little interference, they each use a separate channel (i.e., carrier frequency)
- It is possible to send simultaneously multiple carrier waves over a single copper wire, e.g. 24 digitized voice on a copper wire= T1-carrier system
- A demultiplexer applies a set of filters that each extract a small range of frequencies near one of the carrier frequencies
- Figure 11.2 illustrates the organization
  - A key idea is that the filters used in FDM only examine frequencies
- FDM mechanism will separate the frequency from others without otherwise modifying the signal

Frequency Division Multiplexing

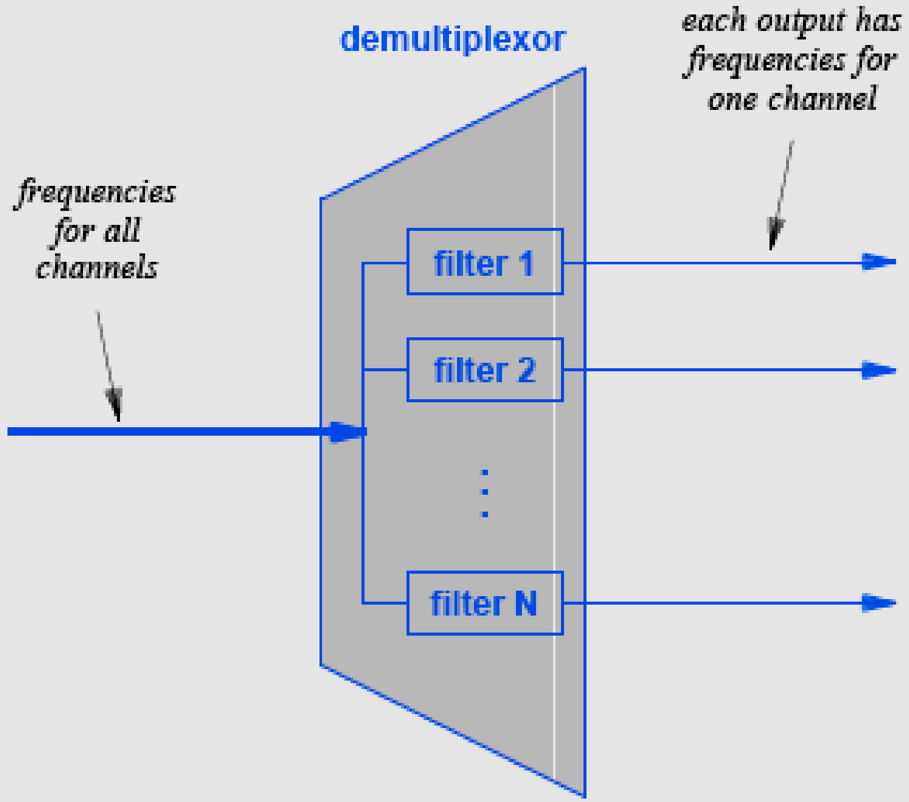
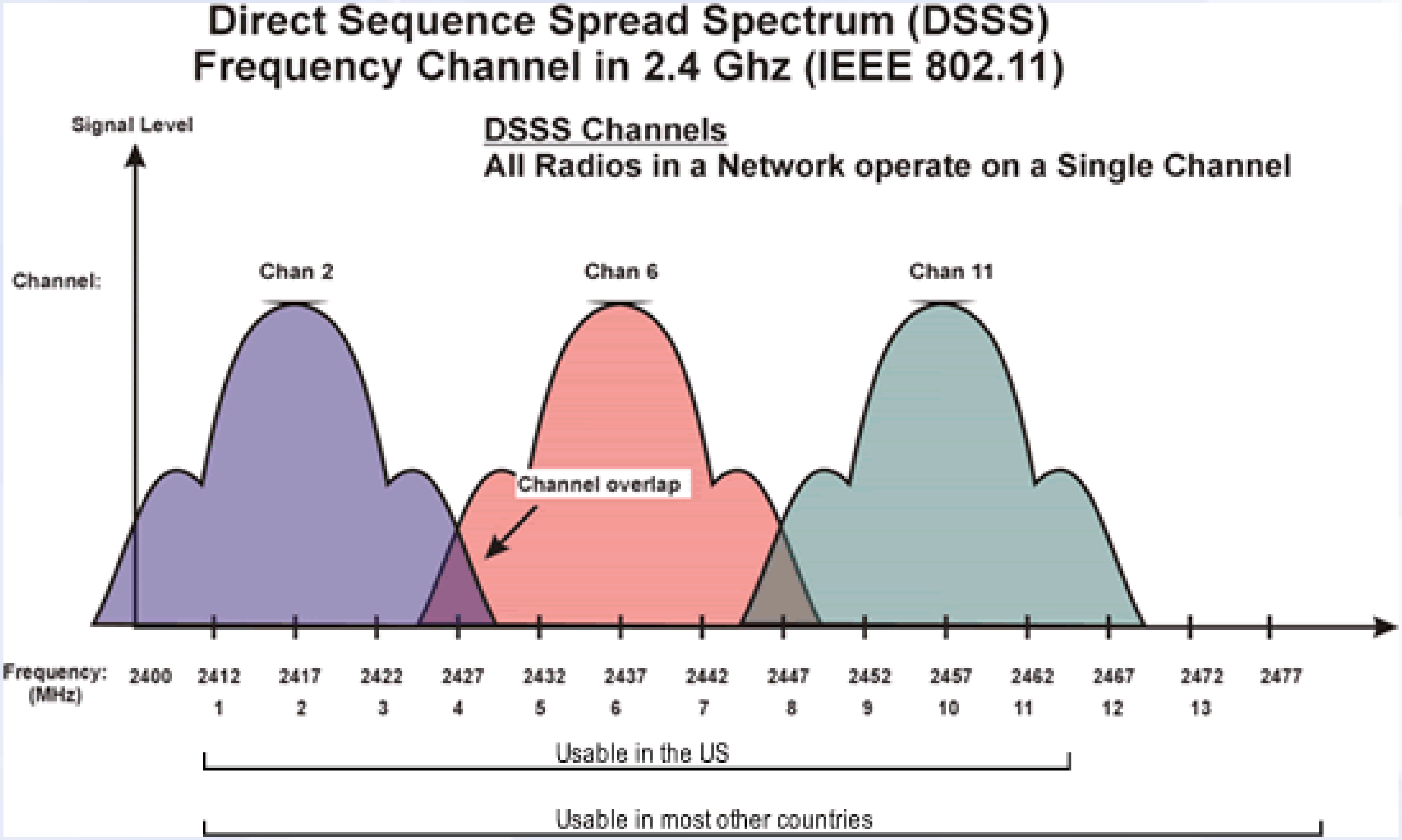


Figure 11.2 Illustration of the basic FDM demultiplexing where a set of filters each selects the frequencies for one channel and suppresses other frequencies.

Example usage of Multiplexing in DSSS (used in cell phone technology)


Direct Sequence Spread Spectrum (DSSS)
Frequency Channel in 2.4 Ghz (IEEE 802.11)

DSSS Channels
All Radios in a Network operate on a Single Channel

Frequency Division Multiplexing

- Advantage of FDM arises from the simultaneous use of a transmission medium by multiple pairs of entities
- We imagine FDM as providing each pair with a private transmission path
  - as if the pair had a separate physical transmission medium
  - Figure 11.3 illustrates the concept
- Practical FDM systems - there are some limitations
  - If the frequencies of two channels are too close, interference can occur
  - Furthermore, demultiplexing hardware that receives a combined signal must be able to divide the signal into separate carriers
  - FCC in USA regulates stations to insure adequate spacing occurs between the carriers
  - Designers choosing a set of carrier frequencies with a gap between them known as a guard band
- Figures 11.4 and 11.5 show an example
  - that allocates 200 KHz to each of 6 channels with a guard band of 20 KHz between each

Frequency Division Multiplexing

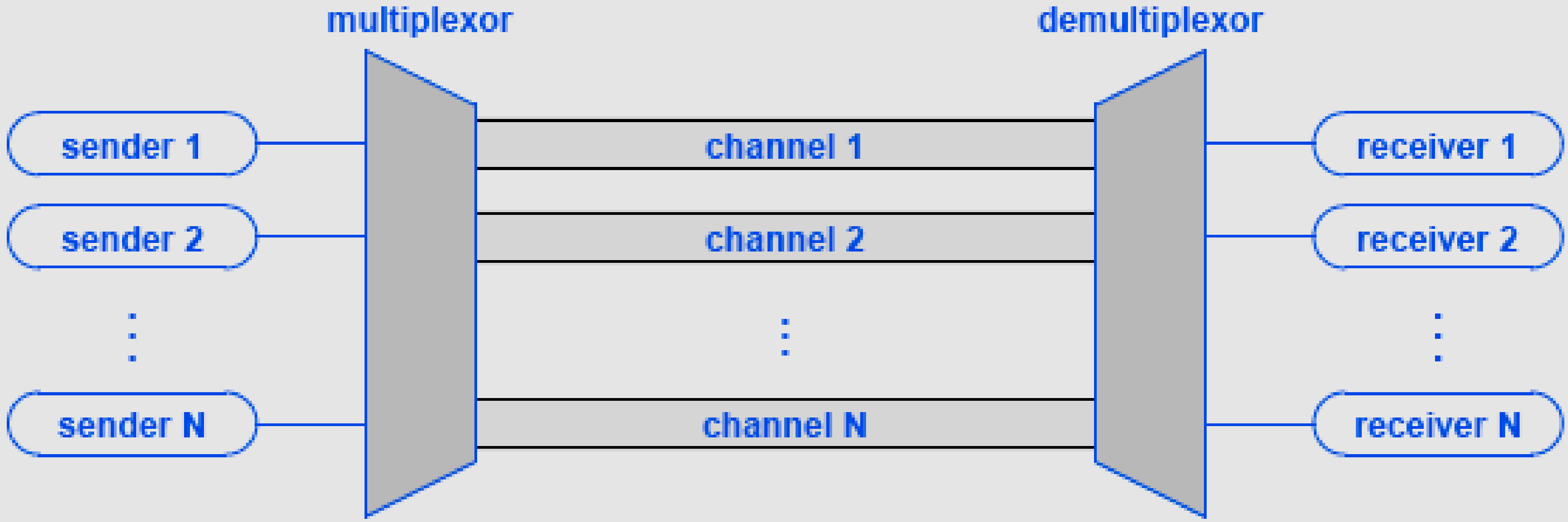


Figure 11.3 The conceptual view of Frequency Division Multiplexing (FDM) as providing a set of independent channels.

Frequency Division Multiplexing

Channel	Frequencies Used
1	100 KHz - 300 KHz
2	320 KHz - 520 KHz
3	540 KHz - 740 KHz
4	760 KHz - 960 KHz
5	980 KHz - 1180 KHz
6	1200 KHz - 1400 KHz

Figure 11.4 An example assignment of frequencies to channels with a guard band between adjacent channels.

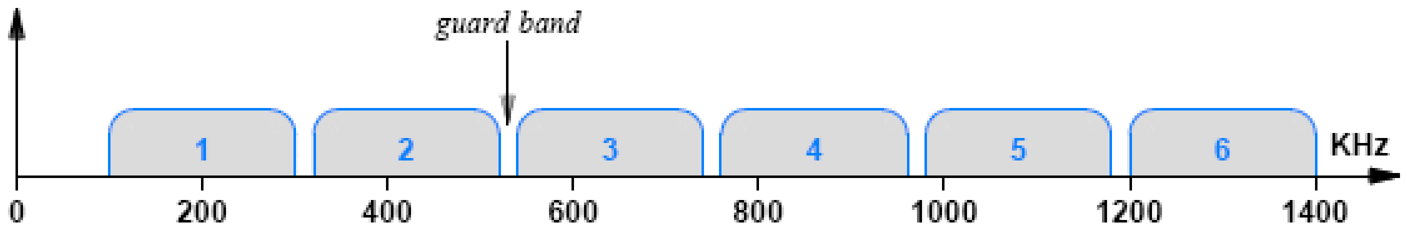


Figure 11.5 A frequency domain plot of the channel allocation from Figure 11.4 with a guard band visible between channels.

Using a Range of Frequencies Per Channel

- Why does the example allocate blocks of frequencies?
- Consider the following characteristics of FDM:
  - Long-lived: FDM, the idea of dividing the electromagnetic spectrum into channels, arose in early experiments in radio
  - Widely used: FDM is used in broadcast radio and television, cable television, and the AMPS cellular telephone
  - Analog: FDM multiplexing and demultiplexing hardware accepts and delivers analog signals
    - Even if a carrier has been modulated to contain digital information, FDM hardware treats the carrier as an analog wave
  - Versatile: Because it filters on ranges of frequency without examining other aspects of signals, FDM is versatile

Using a Range of Frequencies Per Channel

- The analog characteristic has the disadvantage of making FDM susceptible to noise and distortion
- Most FDM systems assign each sender and receiver pair a range of frequencies
- FDM has the ability to choose how the frequencies can be used
- There are two primary ways that systems use a range of frequencies
  - Increase the data rate
  - Increase immunity to interference
- To increase the overall data rate
  - a sender divides the frequency range of the channel into K carriers
  - and sends 1/K of the data over each carrier

Using a Range of Frequencies Per Channel

- A sender can perform FDM within an allocated channel
  - Sometimes, the term subchannel allocation refers to the subdivision
- To increase immunity to interference
  - a sender uses a technique known as spread spectrum
- Various forms are suggested, but basic idea is
  - divide the range of the channel into K carriers
  - transmit the data spread(using secret pattern) over multiple channels
  - allow a receiver to use a copy compose the data that arrives using the same spread pattern used by the sender
- The scheme works well in cases where noise is likely to interfere with some frequencies at a given time

The Godmother of Spread Spectrum - Hedy Lamarr

Hierarchical FDM

- Flexibility in FDM arises from the ability of hardware to shift frequencies
- If a set of incoming signals all use the frequency range between 0 and 4 KHz
  - multiplexing hardware can leave the first stage as is
  - map the second onto the range 4 KHz to 8 KHz
  - map the third onto the range 8 KHz to 12 KHz, and so on
- Hierarchy in FDM multiplexors is that each maps its inputs to a larger, continuous band of frequencies
- Figure 11.6 illustrates the concept of hierarchical FDM

Hierarchical FDM

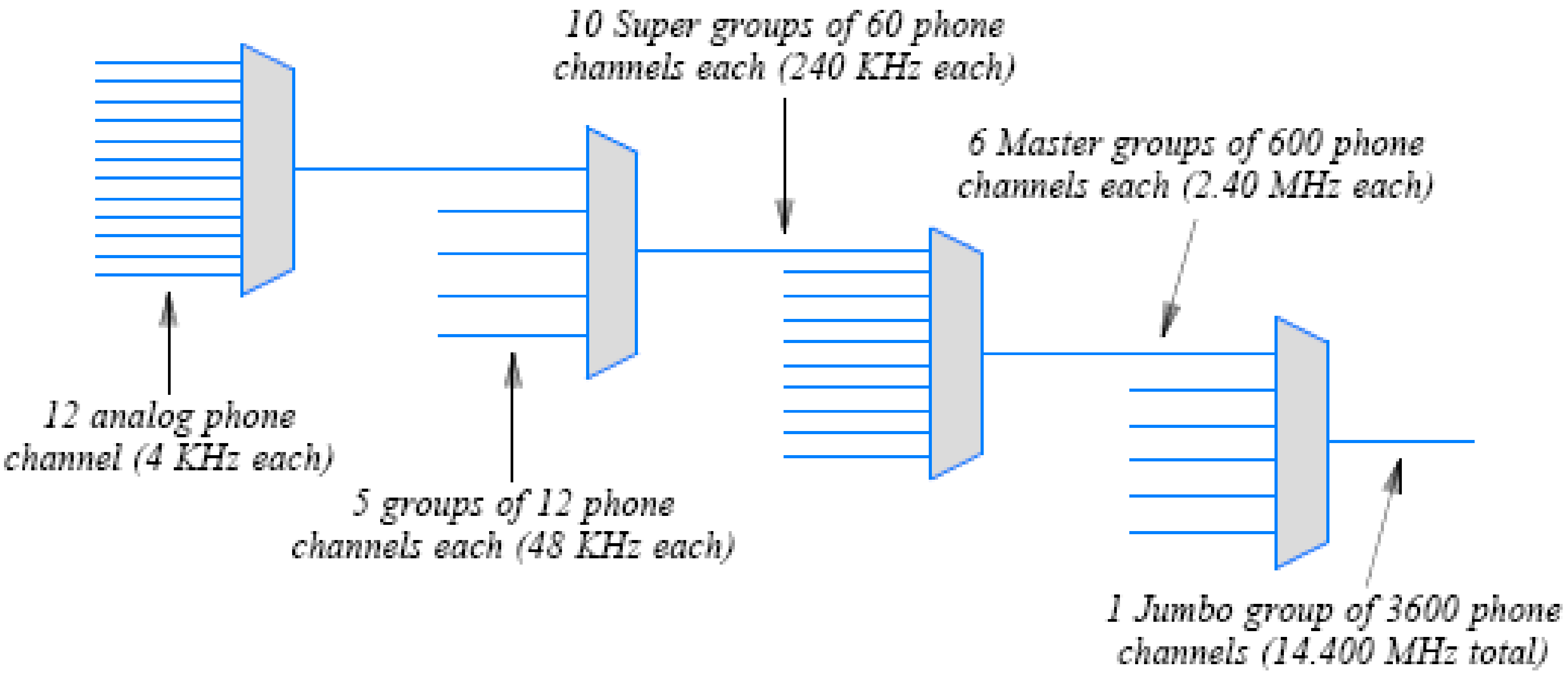


Figure 11.6 Illustration of the FDM hierarchy used in the telephone system.

Wavelength Division Multiplexing (WDM)

- WDM refers to the application of FDM to optical fiber
  - some sources use the term Dense WDM (DWDM) to emphasize that many wavelengths of light can be employed
- The inputs and outputs of such multiplexing are wavelengths of light
  - denoted by the Greek letter λ, and informally called colors
- When white light passes through a prism
  - colors of the spectrum are spread out
- If a set of colored light beams are each directed into a prism at the correct angle
  - the prism will combine the beams to form a single beam of white light

Wavelength Division Multiplexing

- Prisms form the basis of optical multiplexing and demultiplexing
  - a multiplexor accepts beams of light of various wavelengths and uses a prism to combine them into a single beam
  - a demultiplexor uses a prism to separate the wavelengths.

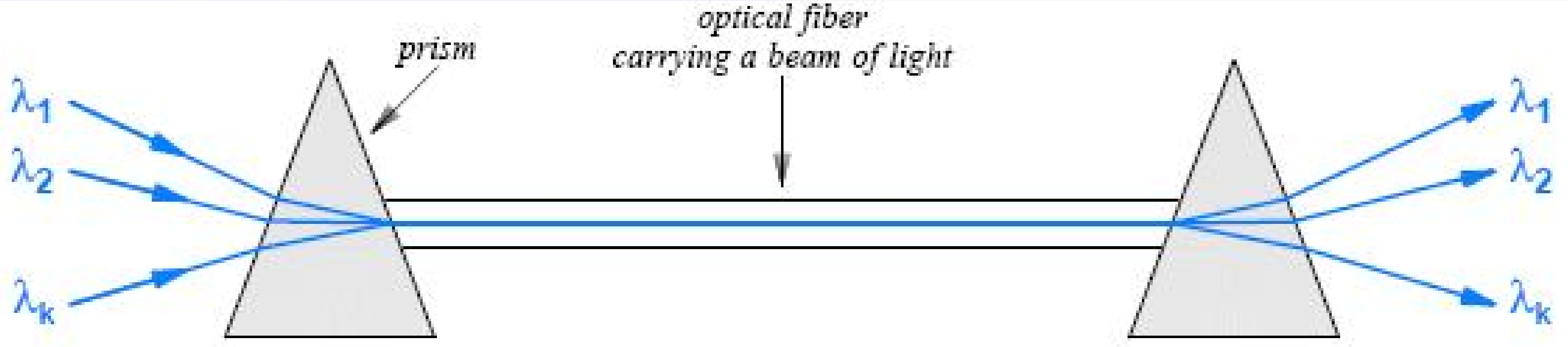


Figure 11.7 Illustration of prisms used to combine and separate wavelengths of light in wavelength division multiplexing technologies.

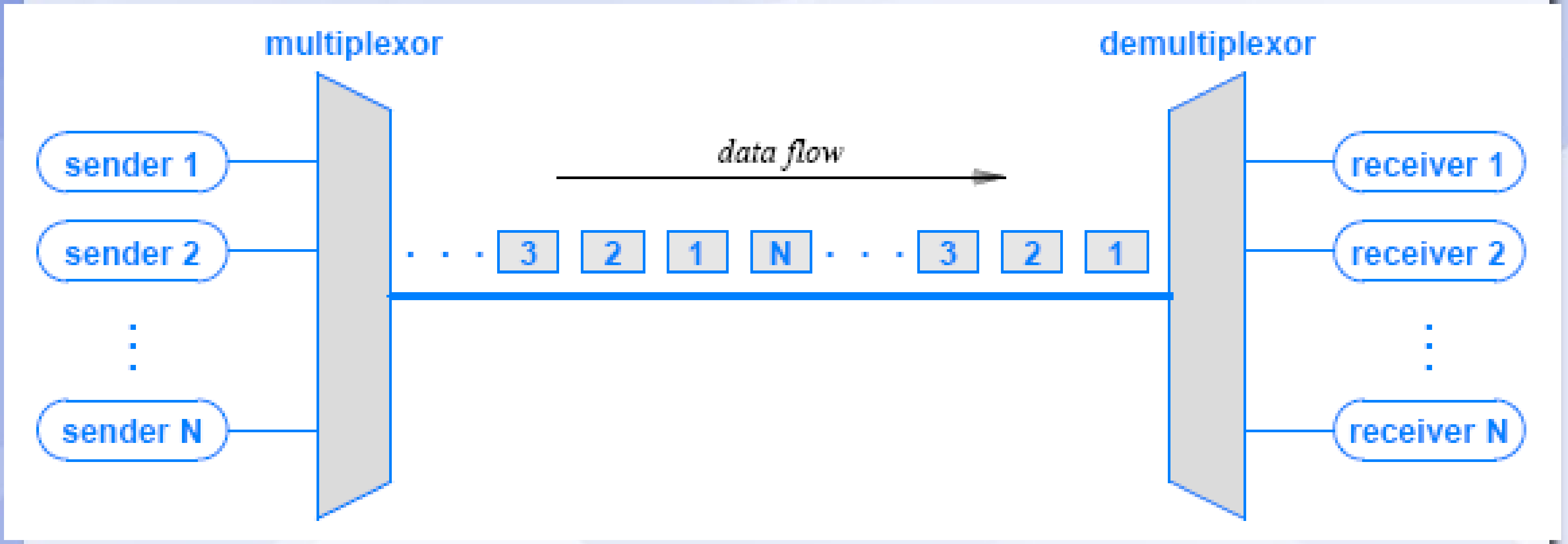
WDM

Each color can be used as a channel

Today's DWDM systems use 50 GHz or even 25 GHz channel spacing for up to 160 channel operation.

Time Division Multiplexing (TDM)

- TDM assigns time slots to each channel repeatedly
  - multiplexing in time simply means transmitting an item from one source, then transmitting an item from another source, and so on
- Figure 11.8 (below) illustrates the concept



Synchronous TDM

- TDM is a broad concept that appears in many forms
  - It is widely used throughout the Internet
- Figure 11.8 is a conceptual view, and the details may vary
- Figure shows items being sent in a round-robin fashion
  - Most TDMs work this way
  - Figure shows a slight gap between items
  - Recall from Chapter 9 that no gap occurs between bits if a communication system uses synchronous transmission
  - When TDM is applied to synchronous networks, no gap occurs between items; the result is known as Synchronous TDM
- Figure 11.9 illustrates how synchronous TDM works for a system of four senders

Synchronous TDM

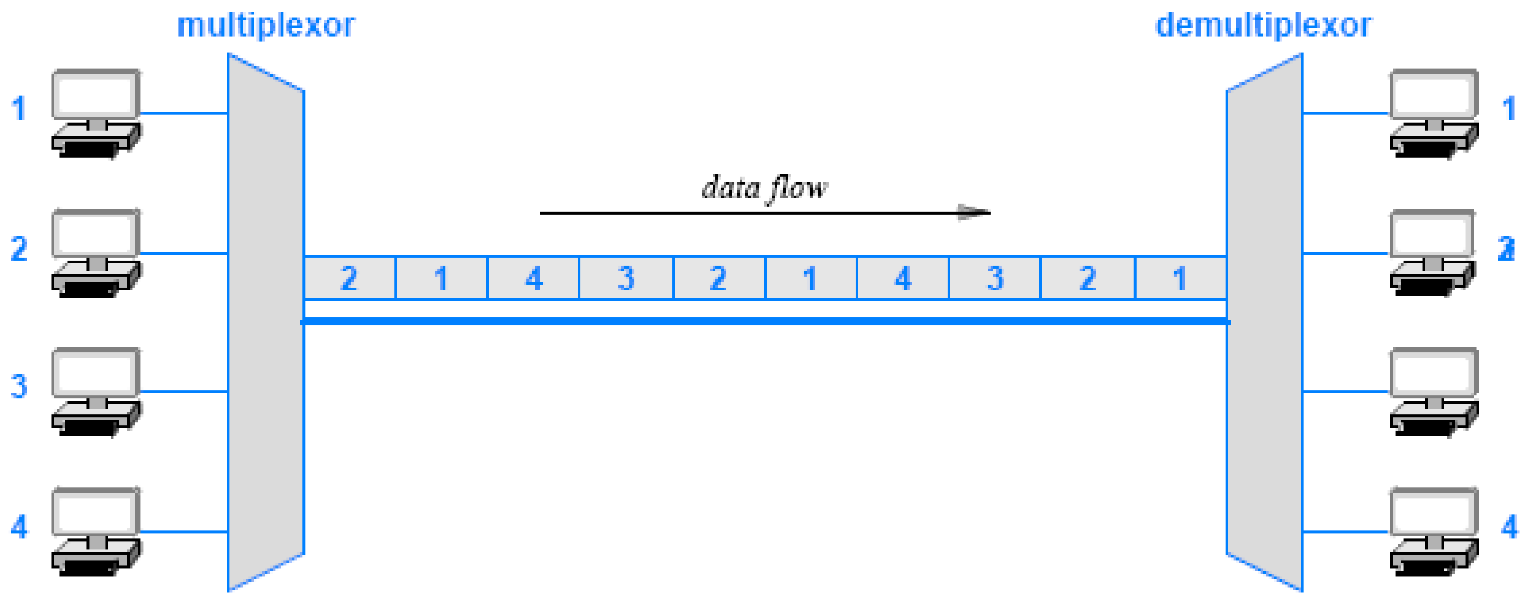


Figure 11.9 Illustration of a Synchronous Time Division Multiplexing system with four senders.

Framing Used in the Telephone System Version of TDM

- Telephone systems use synchronous TDM to multiplex digital streams from multiple phone calls
  - they use the acronym TDM to refer to the specific form of TDM used to multiplex digital telephone calls
- The phone system TDM includes an interesting technique
  - to insure that a demultiplexer stays synchronized with the multiplexer
- Why is synchronization needed?
  - observe that a synchronous TDM sends one slot after another without any indication of the output to which a given slot occurs
  - A demultiplexer cannot tell where a slot begins– a slight difference in the clocks used to time bits can cause a demultiplexer to misinterpret the bit stream

Framing Used in the Telephone System Version of TDM

- To prevent misinterpretation, the version of TDM used in the phone system includes an extra framing channel as input
- Instead of taking a complete slot, framing inserts a single bit in the stream on each round
- A demultiplexor extracts data from the framing channel and checks for alternating 0 and 1 bits
- If an error causes a demultiplexor to lose a bit
  - it is highly likely that the framing check will detect the error and allow the transmission to be restarted
- Figure 11.10 illustrates the use of framing bits

Framing Used in the Telephone System Version of TDM

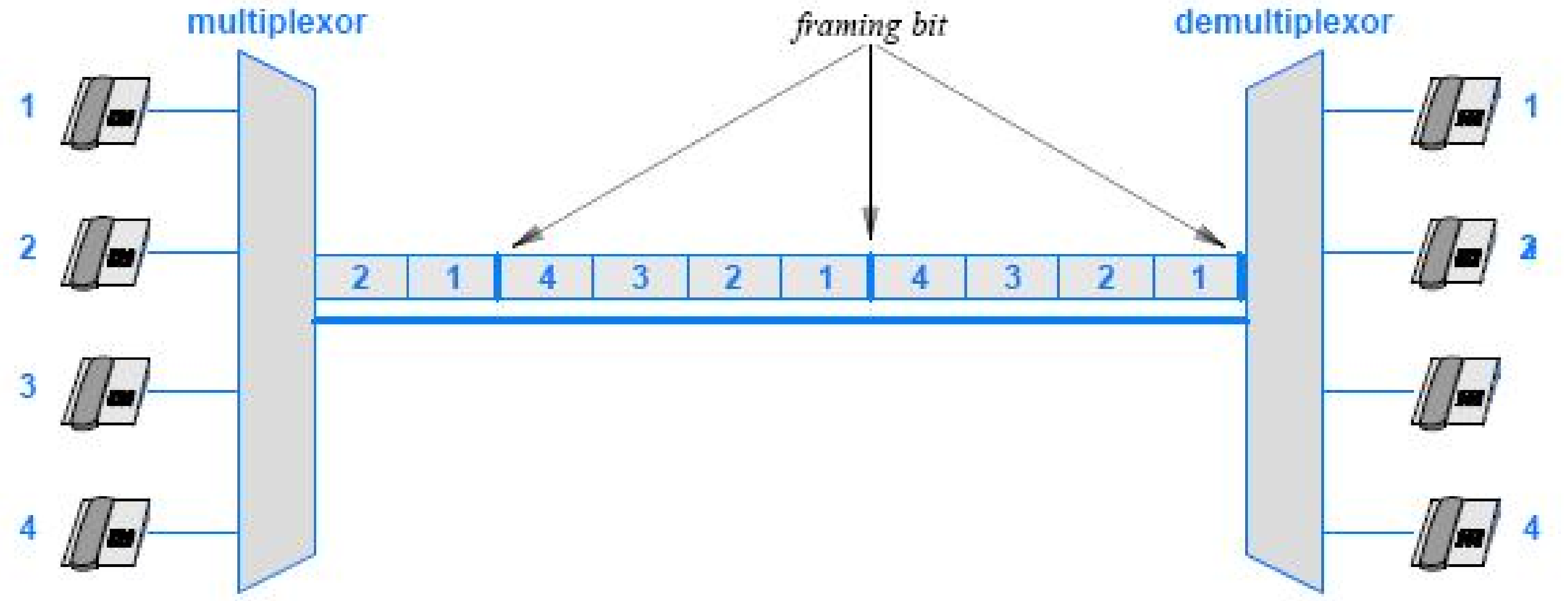


Figure 11.10 Illustration of the synchronous TDM system used by the telephone system in which a framing bit precedes each round of slots.

Hierarchical TDM

- Like FDM, TDM can be arranged in a hierarchy
- The difference is that each successive stage of a TDM hierarchy uses N times the bit rate
  - In FDM, each successive stage uses N times the frequencies
- Additional framing bits are added to the data
  - means that the bit rate of each successive layer of hierarchy is slightly greater than the aggregate voice traffic
- Compare the example TDM hierarchy
  - in Figure 11.11 with the FDM example in Figure 11.6

Hierarchical TDM

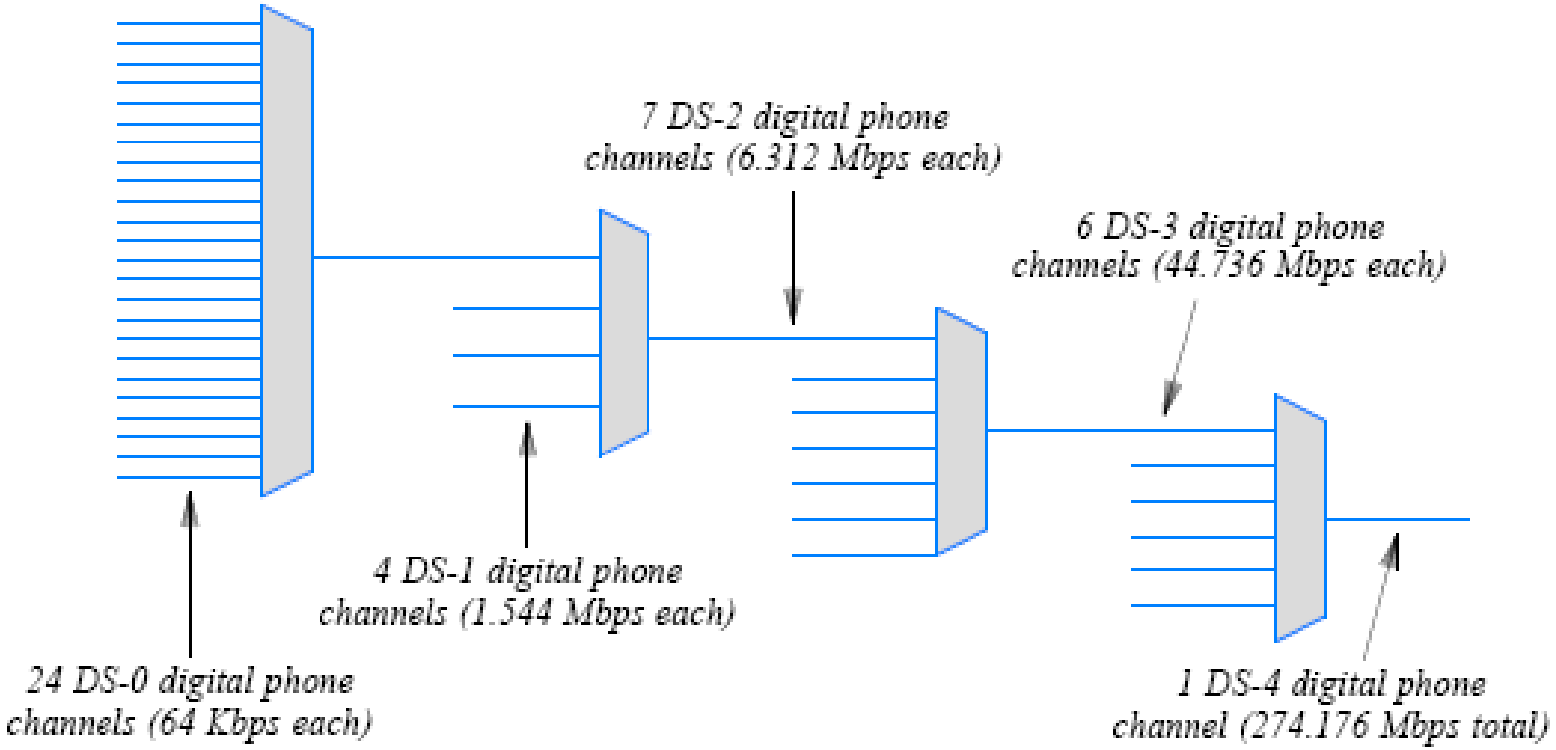


Figure 11.11 Illustration of the TDM hierarchy used in the telephone system.

The Problem with Synchronous TDM: Unfilled Slots

- Synchronous TDM works well if each source produces data at a uniform, fixed rate equal to 1/N of the capacity of the shared medium
- Many sources generate data in bursts, with idle time between bursts
- To understand why, consider the example in Figure 11.12
  - sources on the left produce data items at random
  - the synchronous multiplexor leaves a slot unfilled
    - if the corresponding source has not produced an item by the time the slot must be sent
- In practice, a slot cannot be empty because the underlying system must continue to transmit data
  - the slot is assigned a value (such as zero)
  - and an extra bit is set to indicate that the value is invalid

The Problem with Synchronous TDM: Unfilled Slots

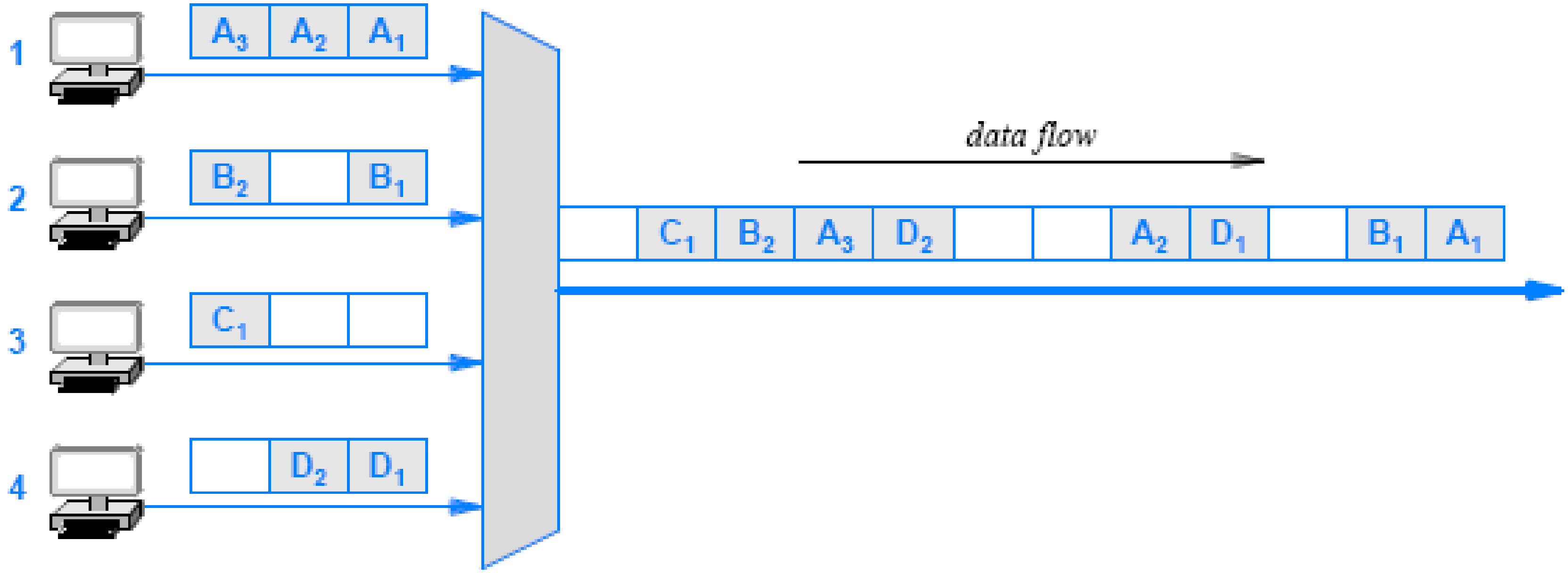


Figure 11.12 Illustration of a synchronous TDM system leaving slots unfilled when a source does not have a data item ready in time.

Statistical TDM

- How can a multiplexing system make better use of a shared medium?
- One technique to increase the overall data rate is known as statistical TDM or statistical multiplexing
  - some literature uses the term asynchronous TDM
- The technique is straightforward:
  - select items for transmission in a round-robin fashion
  - but instead of leaving a slot unfilled, skip any source that does not have data ready
- By eliminating unused slots
  - statistical TDM takes less time to send the same amount of data
- Figure 11.13 illustrates how a statistical TDM system sends the data from Figure 11.12 in only 8 slots instead of 12

Statistical TDM

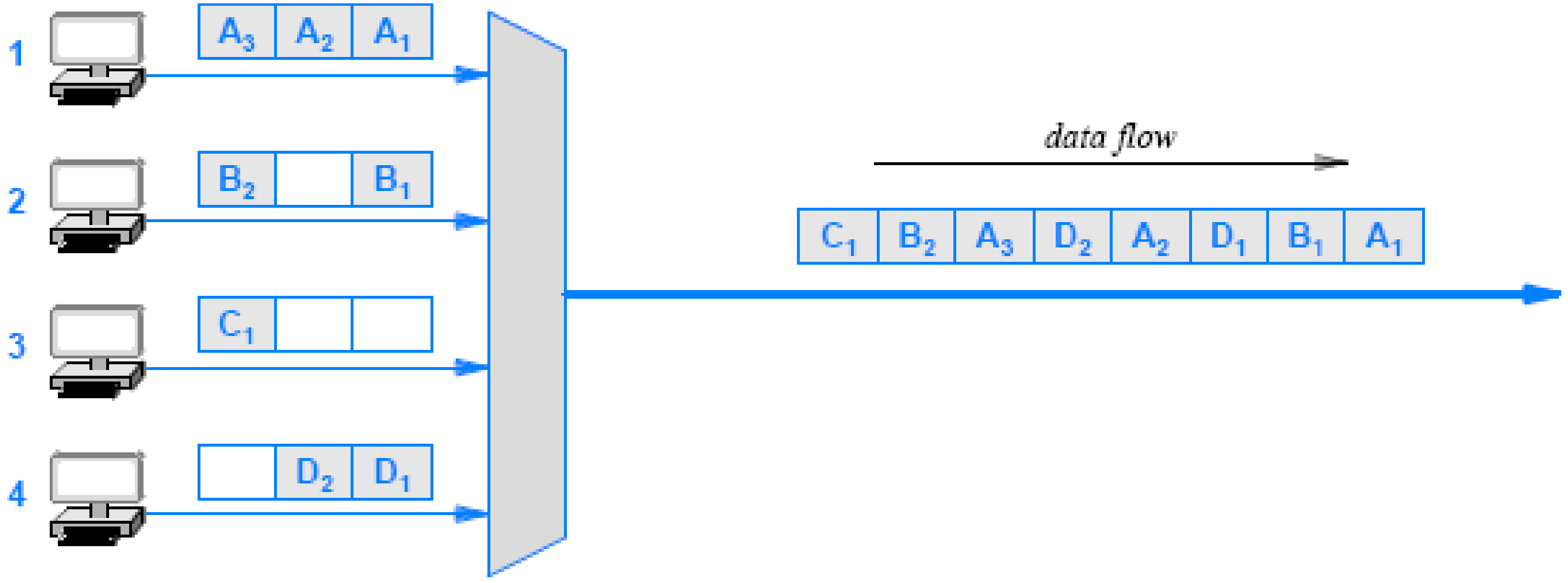


Figure 11.13 Illustration that shows how statistical multiplexing avoids unfilled slots and takes less time to send data.

Statistical TDM

- Statistical multiplexing incurs extra overhead shown below:
  - Consider demultiplexing:
    - In a synchronous TDM system a demultiplexor knows that every N slot corresponds to a given receiver
    - In a statistical multiplexing system, the data in a given slot can correspond to any receiver
  - Each slot must contain the identification of the receiver to which the data is being sent
- Later chapters discuss identification mechanisms
  - that are used with statistical multiplexing in packet switching networks and the Internet

Inverse Multiplexing

- Assume a case where a connection between two points consists of multiple transmission media
  - but no single medium has a bit rate that is sufficient
- At the core of the Internet, for example, service providers need higher bit rates than are available
- To solve the problem, multiplexing is used in reverse
  - spread a high-speed digital input over multiple lower-speed circuits for transmission and combine the results at the receiving end
- Figure 11.14 illustrates the concept

Inverse Multiplexing

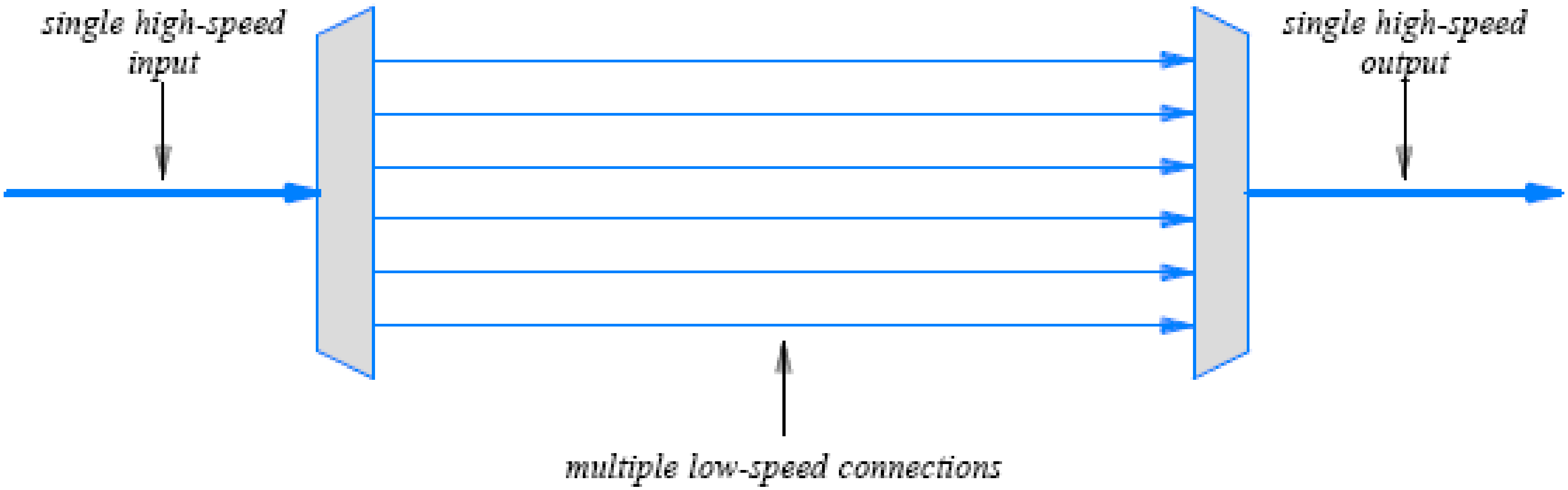
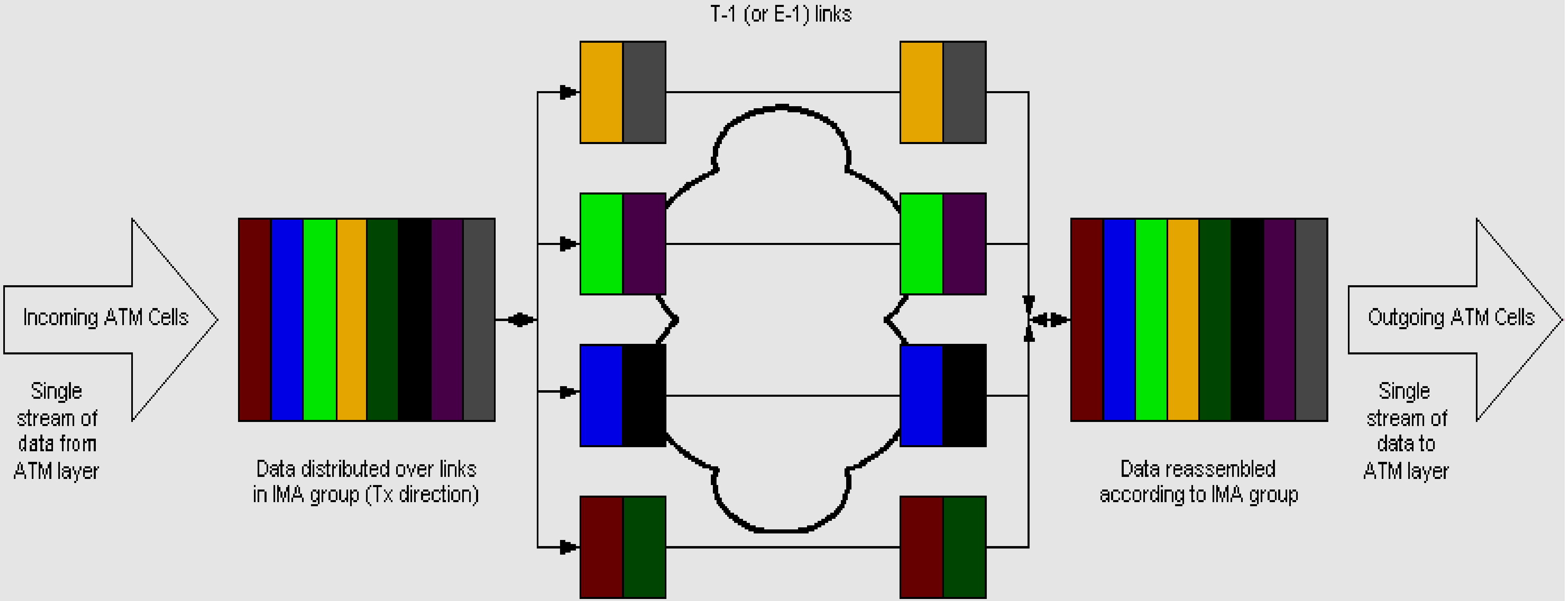


Figure 11.14 Illustration of inverse multiplexing in which a single high-speed digital input is distributed over lower-speed connections for transmission and then recombined to form a copy of the input.

Inverse Multiplexing

- An inverse multiplexor cannot be constructed by connecting the pieces of a conventional multiplexor backward
  - hardware must be designed so that the sender and receiver agree on how data arriving from the input will be distributed over the lower-speed connections
  - to insure that all data is delivered in the same order as it arrived, the system must be engineered to handle cases
    - where one or more of the lower-speed connections has longer latency than others
- Despite its complexity, inverse multiplexing is widely used in the Internet

Example of Inverse Multiplexing



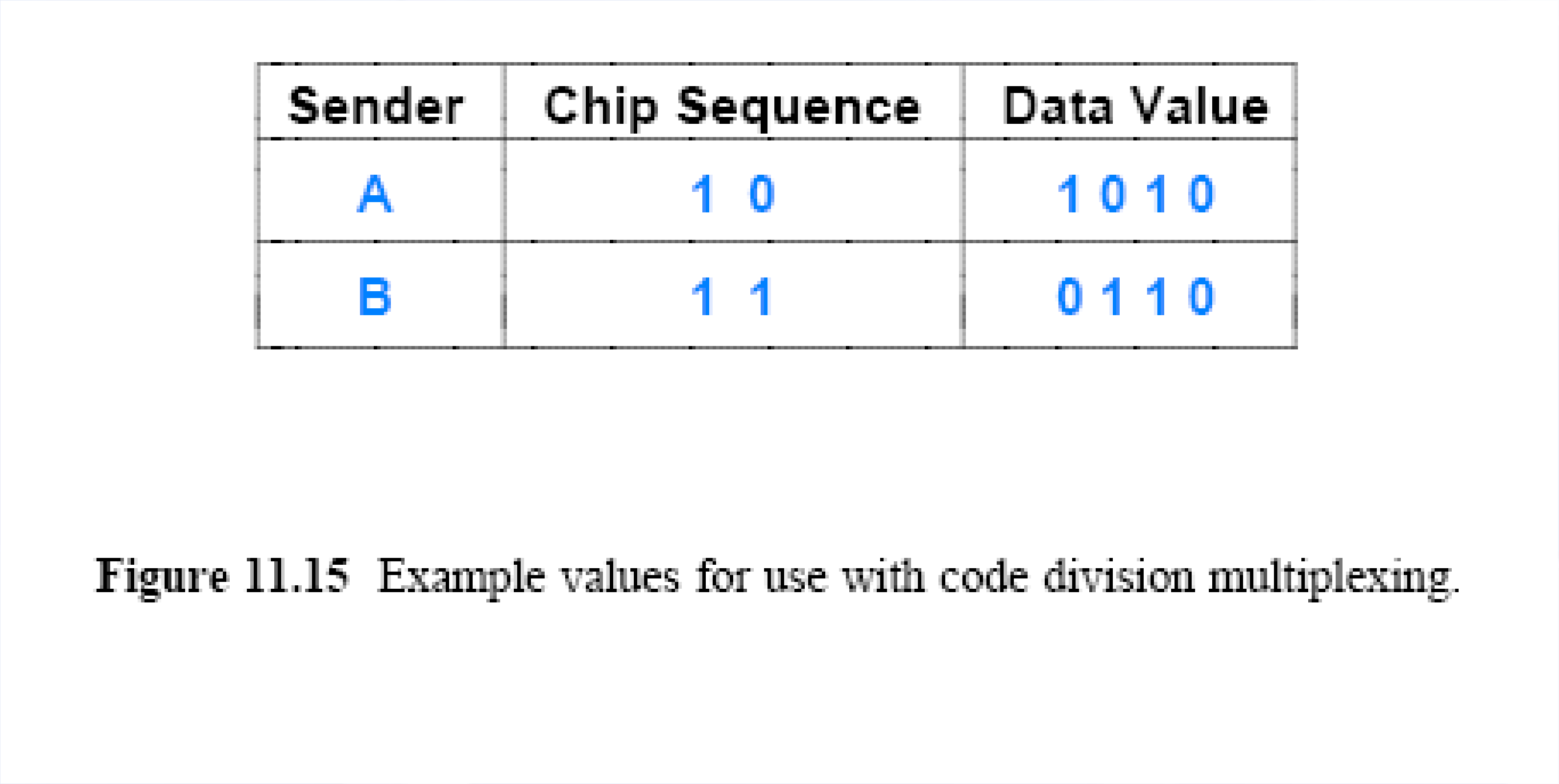
Code Division Multiplexing (CDM)

- CDM used in parts of the cellular telephone system and for some satellite communication
  - The specific version of CDM used in cell phones is known as Code Division Multi-Access (CDMA)
- CDM does not rely on physical properties
  - such as frequency or time
- CDM relies on an interesting mathematical idea
  - values from orthogonal vector spaces can be combined and separated without interference
- Each sender is assigned a unique binary code C_i
  - that is known as a chip sequence
  - chip sequences are selected to be orthogonal vectors
  - (i.e., the dot product of any two chip sequences is zero)

Code Division Multiplexing

- At any point in time, each sender has a value to transmit, V_i
  - The senders each multiply C_i x V_i and transmit the results
- The senders transmit at the same time
  - and the values are added together
- To extract value V_i, a receiver multiplies the sum by C_i
- Consider an example
  - to keep the example easy to understand, use a chip sequence that is only two bits long and data values that are four bits long
  - think of the chip sequence as a vector
- Figure 11.15 lists the values

Code Division Multiplexing



Sender	Chip Sequence	Data Value
A	1 0	1 0 1 0
B	1 1	0 1 1 0

Figure 11.15 Example values for use with code division multiplexing.

Code Division Multiplexing

- The first step consists of converting the binary values into vectors that use -1 to represent 0:

$C_1 = (1, -1) \quad V_1 = (1, -1, 1, -1) \qquad C_2 = (1, 1) \quad V_2 = (-1, 1, 1, -1)$

Multiplying $C_1 \times V_1$ and $C_2 \times V_2$ produces:

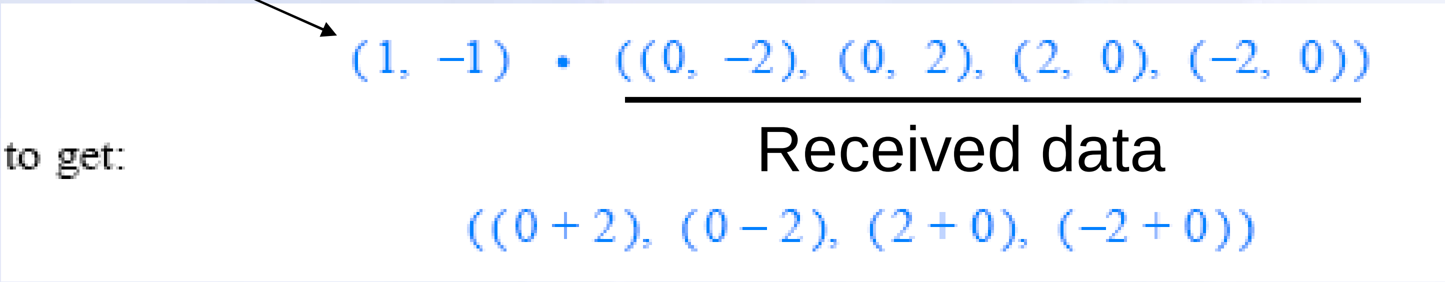
$((1, -1), (-1, 1), (1, -1), (-1, 1)) \qquad ((-1, -1), (1, 1), (1, 1), (-1, -1))$

- If we think of the resulting values as a sequence of signal strengths to be transmitted at the same time
  - the resulting signal will be the sum of the two signals

$$\begin{array}{rrrrrrrrr} & 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \\ + & -1 & -1 & 1 & 1 & 1 & 1 & -1 & -1 \\ \hline & 0 & -2 & 0 & 2 & 2 & 0 & -2 & 0 \end{array}$$

Code Division Multiplexing

- A receiver treats the sequence as a vector
  - computes the product of the vector and the chip sequence
  - treats the result as a sequence, and converts the result to binary by interpreting positive values as binary 1 and negative values as 0
- Thus, receiver number 1 computes:



$$\overset{C_1}{(1, -1)} \cdot \underbrace{((0, -2), (0, 2), (2, 0), (-2, 0))}_{\text{Received data}}$$

to get:

$$((0+2), (0-2), (2+0), (-2+0))$$

- Interpreting the result as a sequence produces: (2 -2 2 -2)
  - which becomes the binary value: (1 0 1 0)
  - note that 1010 is the correct value of V_1
  - receiver 2 will extract V_2 from the same transmission

Code division multiple access (CDMA) is a channel access method utilized by various radio communication technologies.