Lesson 25: Multiplexing

Objectives:
(a) Explain why multiplexing techniques are necessary in telemetry, telephone systems, radio, and TV broadcasting and internet access- various communication systems.
(b) Describe spatial multiplexing
(c) Describe how frequency division multiplexing (FDM) and time division multiplexing (TDM) allow multiple signals to be transmitted over the same channel

1. Introduction

Up until now, we've always considered one transmitter sending one signal over one channel (or communication medium) to one receiver. But in real life, to efficiently utilize the bandwidth of the channel, we often want to send multiple signals over one channel. In this lesson, we will look at several techniques to combine multiple signals for transmission over one channel. These techniques are known as *multiplexing techniques*.

2. Spatial Multiplexing and Frequency Division Multiplexing (FDM)

Multiplexing is the process of sharing a single communication channel (or medium) for transmission of multiple signals. Why is this important?

1. Often in communication (e.g. *telephone* systems) it is necessary or desirable to transmit more than one voice or data signal simultaneously.
2. Telemetry: Many physical systems have multiple *sensors* which generate data that must be transmitted back to a monitor or control system. (For example, chemical plants, space shuttle, etc.) Oftentimes it is not practical or *cost-effective* to have a separate communication channel for each sensor.

An overview of signal multiplexing is shown in Figure 1. Note that the channel (or medium or link) shown in the figure can be a wire or free space (wireless communication) and

- A *multiplexer (MUX)*is a component that combines multiple signals into a single data stream, and
- A *de-multiplexer (DeMux)is a* component that separates a single data stream into multiple signals.

In this lesson, we will introduce three basic types of multiplexing techniques: *spatial multiplexing*, *frequency division multiplexing (FDM)*, and *time division multiplexing (TDM).*

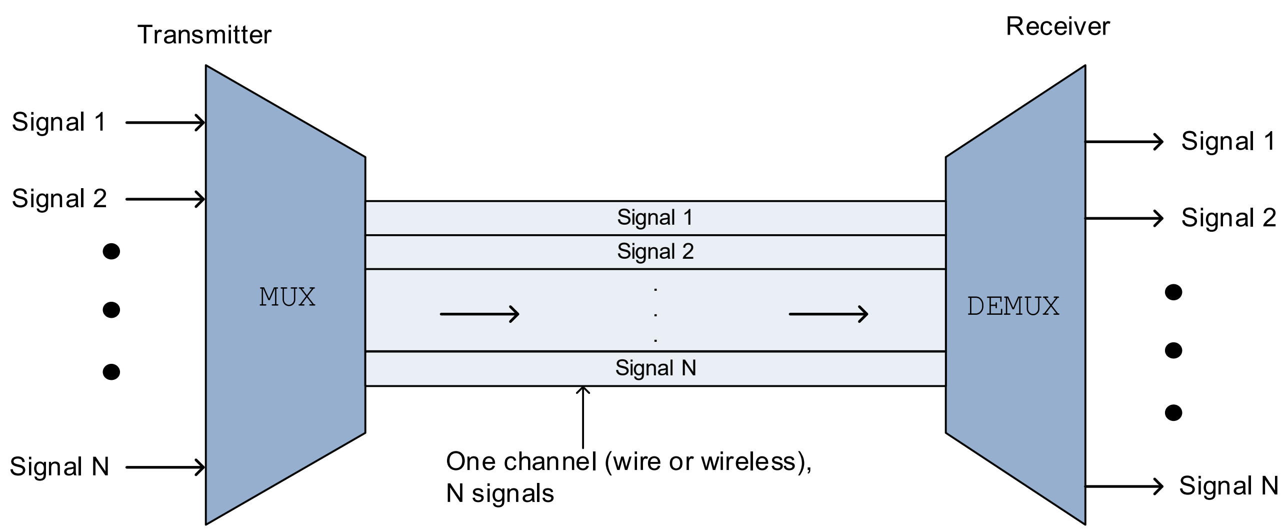


Fig. 1. Overall concept of transmitting multiple signals over one channel with multiplexing.
(Adapted from Forouzan, B., *Data Communication and Networking*, 5th ed.)

Spatial Multiplexing:

Transmits multiple *wireless* signals on a common frequency by either using *low* power transmissions or carefully controlling radiation patterns to *direct* the signals to different locations so they don't interfere with each other. This technique is also known as "*frequency reuse*". This, for example, is why many radio stations across the country can transmit at the same frequency, because they are separated far enough geographically and the transmissions are low power. Another way to "aim" signals in a particular direction is through beam-forming. Essentially, by coordinating the transmission of multiple antennas, overlap between the transmissions can be designed to maximize power received at a particular location. This is used in WiFi5 and WiFi6 to "point" a transmission to a particular device.

Frequency Division Multiplexing (FDM):

When *Frequency Division Multiplexing (FDM)* technique is used, multiple signals share the same channel by transmitting at different *carrier frequencies* within the channel's *bandwidth* (i.e. they share the bandwidth of a common communication channel). We use *modulation* with separate carrier frequencies equally spaced over the frequency range.

- FDM is usually used for *analog* data.
- Some of the communication systems that use FDM include *cable TV* (each signal gets a 6MHz channel), *FM stereo broadcasting* (for Left and Right, and for Radio Data System (RDS)).

Example 1: Assume that a typical voice signal has frequencies as high as 4 kHz, and we need to transmit three separate voice signals simultaneously. Using Frequency Division Multiplexing with Amplitude Modulation, choose three carrier frequencies such that the voice signals can be combined without interfering with each other.

- First, we note that the modulated version of each of these signals will occupy 8 kHz of bandwidth in the frequency domain, since the AM signal contains two sidebands (a copy and a mirror image of the original signal). Therefore the most efficient method will place the signals immediately next to each other, requiring a total of 24 kHz (i.e. 8 kHz per signal).
- Using modulation, we can choose carrier frequencies to space the signals in a desired 24 kHz range. For example, we could select the following
    - Assign voice signal 1 to 16 – 24 kHz bandwidth → modulated it with $f_{c1} = 20$ kHz
    - Assign voice signal 2 to 24 – 32 kHz bandwidth → modulated it with $f_{c2} = 28$ kHz
    - Assign voice signal 3 to 32 – 40 kHz bandwidth → modulated it with $f_{c3} = 36$ kHz
- Finally, combine these three modulated signals and send it via a common channel. Note that in the case of radio transmission, we can achieve the multiplexing effect with a single transmitter sending the combined signal or three different transmitters (e.g. different radio stations) transmitting each of their respective modulated signals, since they will combine together in free space.
- The overall process is illustrated in Figure 2.

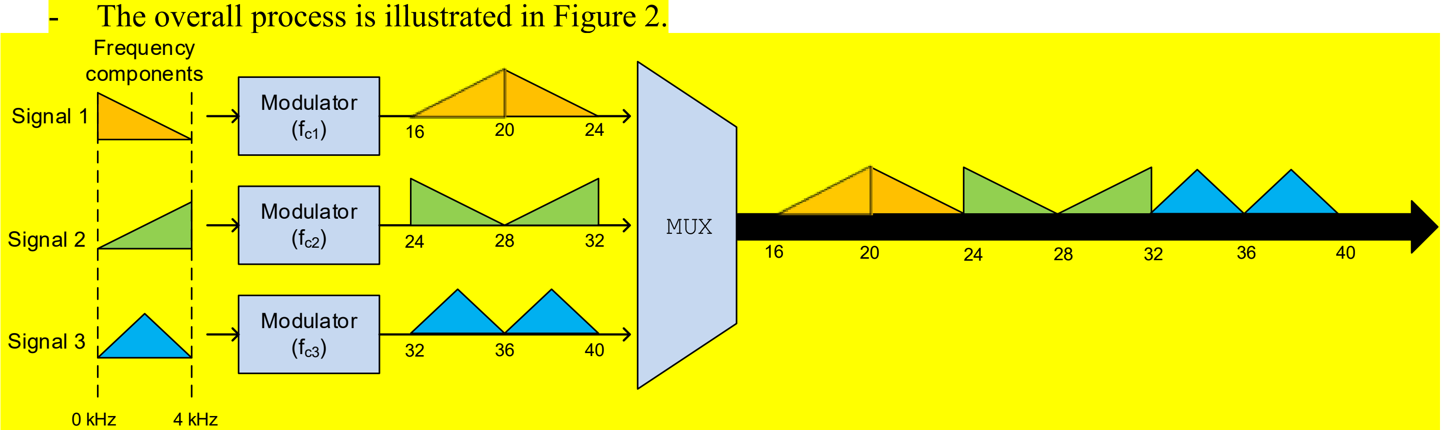


Fig. 2. Combining three low bandwidth voice signals into one high bandwidth channel using FDM.
(Adapted from Forouzan, B., *Data Communication and Networking*, 5th ed.)

Example 2: Due to budget cuts, you're told that you must achieve the same task with only half the bandwidth! Determine a method to combine the three voice signals into a channel with a bandwidth of 12 kHz, from 20 to 32 kHz. Show the configuration, using the frequency domain.

- We'll follow the same process, but we'll use band-pass filters (BPF) to remove half of the modulated signals before transmitting. We can do this, because the lower sideband is just a mirror image of the upper sideband, and so we don't need to transmit both of them to communicate the required information.
- First, divide the bandwidth of the channel into three separate frequency ranges: 20 – 24kHz, 24 – 28 kHz, and 28 – 32 kHz.
- Then, assign each range to a signal and shift the original signals to assigned ranges. This is done with modulation with a carrier frequency. For this example,
  - Assign voice signal 1 to 20 – 24 kHz bandwidth → modulated it with f_{c1} = 20 kHz
  - Assign voice signal 2 to 24 – 28 kHz bandwidth → modulated it with f_{c2} = 24 kHz
  - Assign voice signal 3 to 28 – 32 kHz bandwidth → modulated it with f_{c3} = 28 kHz
- Then use a band-pass filter (BPF) to remove the lower sideband. For example, in the figure below the BPF for signal 1 would have a lower cutoff frequency of 20 kHz and and upper cutoff frequency of 24 kHz.
- Finally, combine these three modulated signals and send via a common channel.
- This process, known as "Single Sideband Transmission" is illustrated in Figure 3.

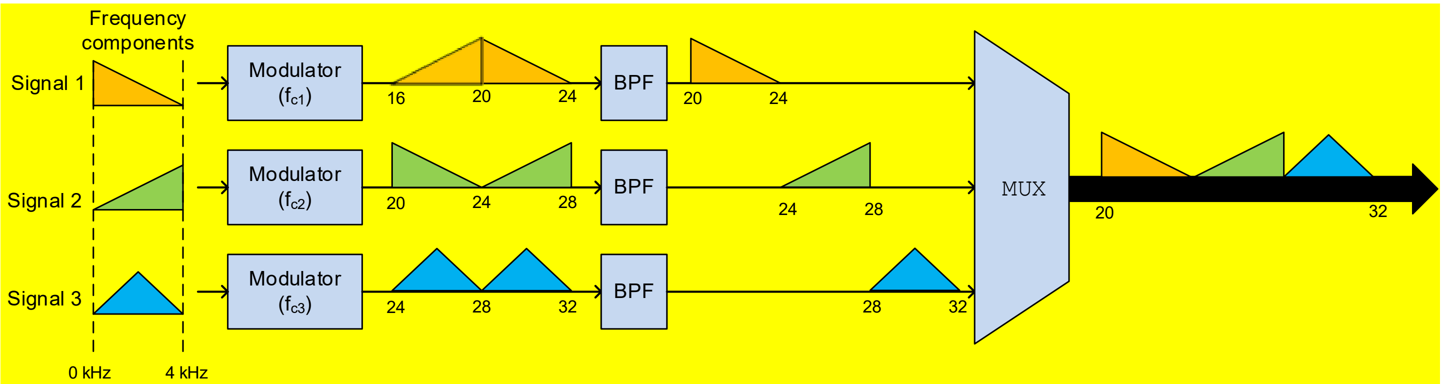


Fig. 3. Combining three low bandwidth voice signals into one high bandwidth channel using FDM with Band-pass Filters (i.e. "Single Sideband Transmission").
(Adapted from Forouzan, B., *Data Communication and Networking*, 5th ed.)

Note: In the previous two examples, we had the signals immediately next to each other on the EM spectrum. In most practical applications we include ____________ bands, which are unused bands of frequencies between radio bands, intended to prevent interference.

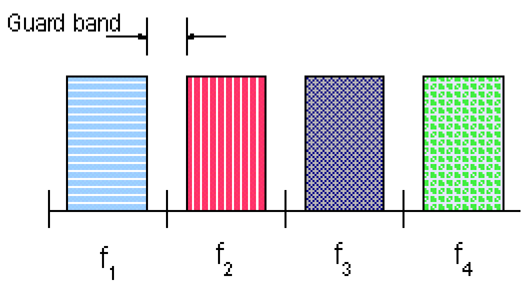


Fig. 4. Guard bands between transmissions help to prevent interference.
(From https://www.telecomabc.com/g/guardband.html.)

3. Time Division Multiplexing (TDM)

When *Time Division Multiplexing (TDM)* technique is used, multiple signals share the same channel by *taking turns* transmitting. Data is broken up into *frames* and assigned to time slots. (Like cars merging in a lane). This technique is primarily used for digital data.

- Each signal uses the *entire bandwidth* of the channel when transmitting.
- On the receiving end, the demultiplexing process requires *synchronization* of the frames. This is often accomplished through a *sync* pulse.
- To help detecting transmission errors, additional error detection code (i.e. *parity* bits) may be added to each frame. [We'll cover this during an upcoming lecture on error detection and correction.]

A conceptual illustration of TDM is shown in Figure 4.

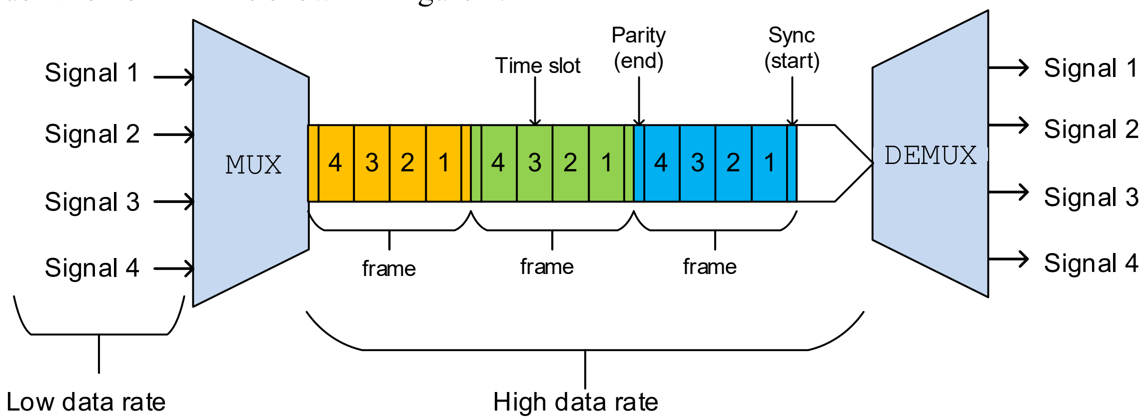
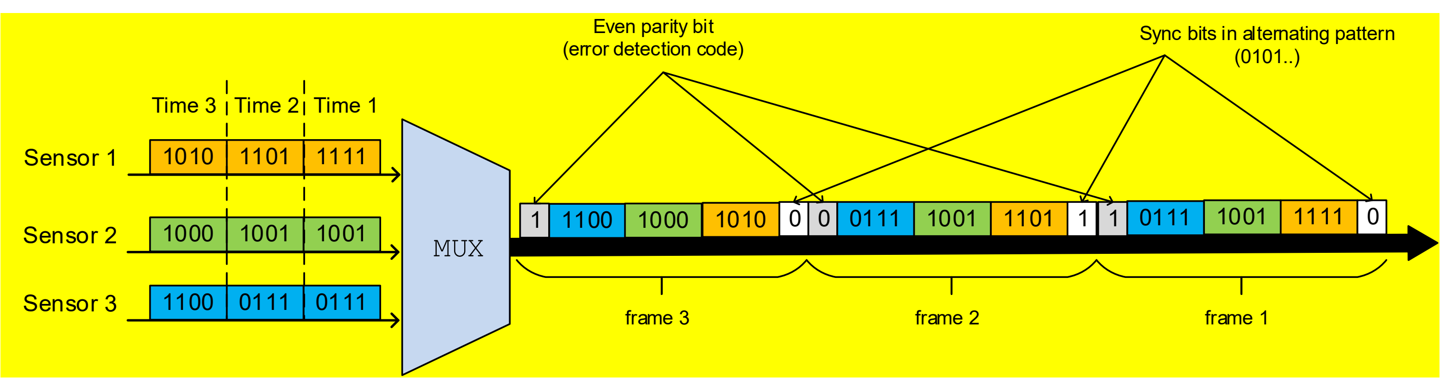


Fig. 5. Conceptual view of TDM.
(Adapted from Forouzan, B., *Data Communication and Networking*, 5th ed.)

Example 3: UAV sensor reports (altitude, battery level, speed) are being sent using TDM. Each sensor sends a 4-bit data packet at each time step. A single sync bit is included at the beginning of each frame, which follows an alternating pattern (i.e. if one frame starts with a 0, the next will start with a 1). Parity bits are included at the end of each frame, and the sync bit is not included when calculating the parity bit.

Assuming that the first 3 data packets from each sensor are shown in the table below, show the data stream in binary on the channel.

	Time 1	Time 2	Time 3
Altitude (m) – Sensor1	15 (1111)	13 (1101)	10 (1010)
Battery level (*10%) – Sensor 2	9 (1001)	9 (1001)	8 (1000)
Speed (m/s) – Sensor 3	7 (0111)	7 (0111)	12 (1100)



Note that in this figure, the bitstreams are shown in the form with time 1 to the right and the first frame to the right, i.e. the order in which they would be received on the receiver end. However, each individual frame is written with most significant byte to the left and least significant byte to the right, as usual.

Questions: Assuming that the data rate of the channel is 100 kbps.

a. What is the frame rate (frame per second – fps) of the channel?

$$frame\ rate = \frac{100 \times 10^3}{14} = 7142.86\ or\ 7142\ fps$$

b. What is the maximum bit rate for each sensor?

$$bit\ rate = 7142 \times 4 = 28568\ bps$$