King Fahd University of Petroleum & Minerals
Computer Engineering Dept

COE 342 – Data and Computer Communications

Term 021

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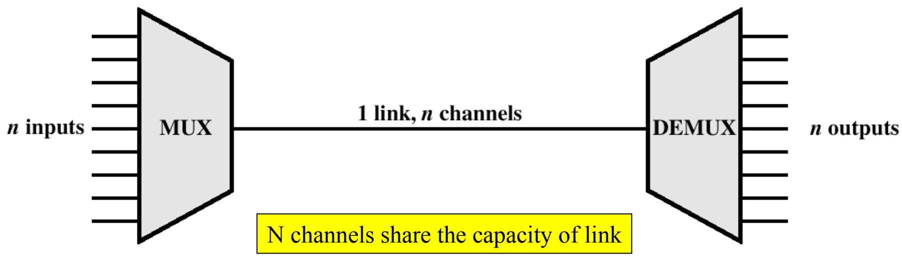
Lecture Contents

1. Frequency-Division Multiplexing
2. Synchronous Time-Division Multiplexing
3. Statistical Time-Division Multiplexing

What is MULTIPLEXING?

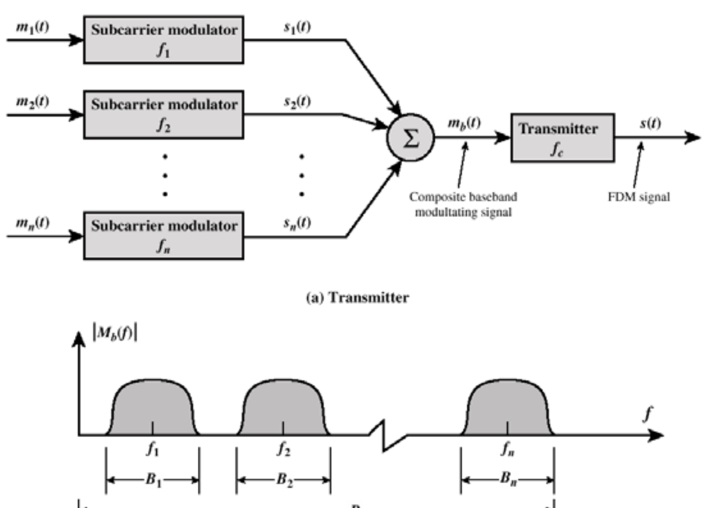
- A generic term used where more than one application or connection share the capacity of one link
- Why?
  - To achieve better utilization of resources



N channels share the capacity of link

Frequency-Division Multiplexing - Transmitter

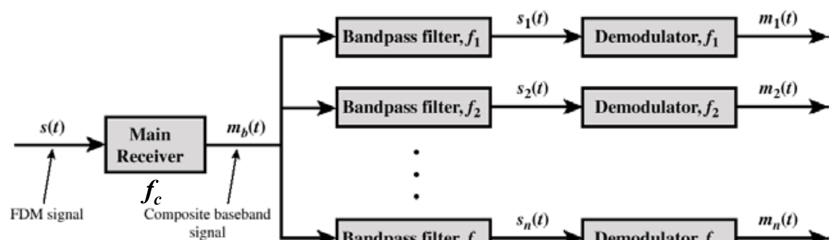
- $m_i(t)$: analog or digital information
- Modulated with subcarrier f_i ➔ $s_i(t)$
- $m_b(t)$ composite baseband modulating signal
- $m_b(t)$ modulated by f_c ➔The overall FDM signal s(t)



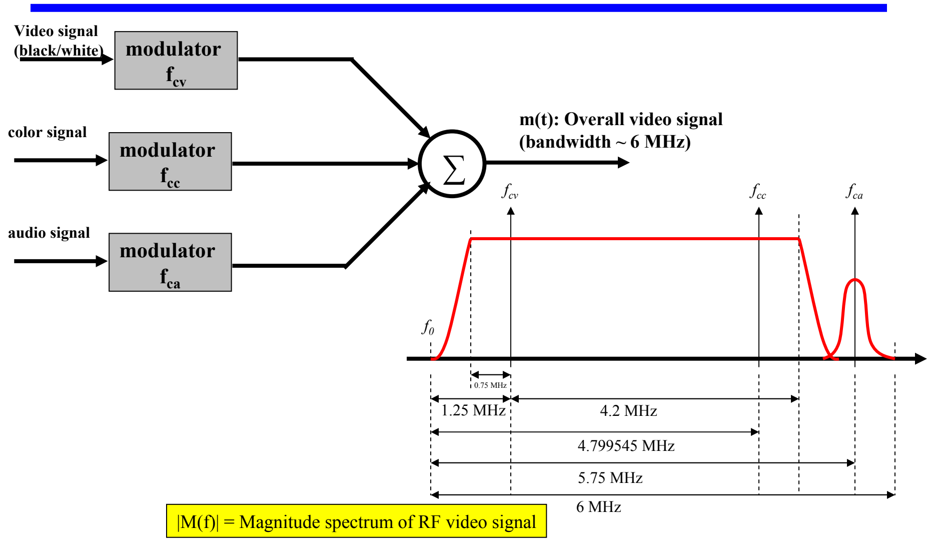
Spectrum function of composite baseband modulating signal $m_b(t)$

Frequency-Division Multiplexing - Receiver

- $m_b(t)$ is retrieved by demodulating the FDM signal s(t) using carrier f_c
- $m_b(t)$ is passed through a parallel bank of bandpass filters – centered around f_i
- The output of the i^{th} filter is the i^{th} signal $s_i(t)$
- $m_i(t)$ is retrieved by demodulating $s_i(t)$ using subcarrier f_i



Frequency-Division Multiplexing – Example 1: Cable TV



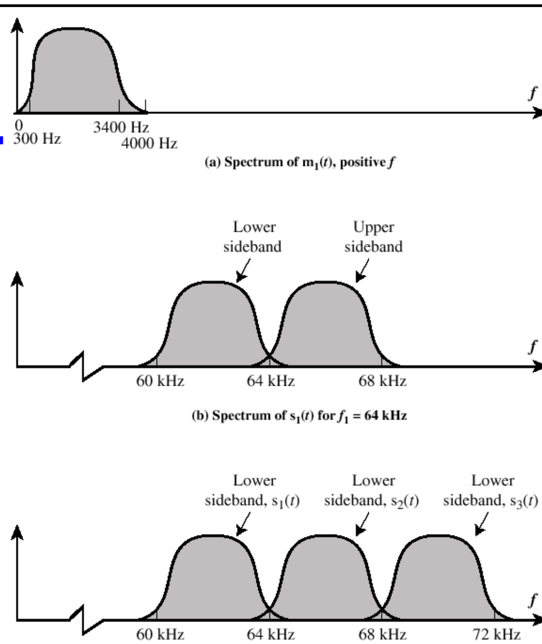
Frequency-Division Multiplexing – Example 1: Cable TV – cont'd

- Cable has BW ~ 500 MHz ➔ 10s of TV channels can be carried *simultaneously* using FDM
- Table 8.1: Cable Television Channel Frequency Allocation (partial): 61 channels occupying bandwidth up to 450 MHz

Channel No	Band (MHz)	Channel No	Band (MHz)	Channel No	Band (MHz)
2	54-60	22	168-174	42	330-336
3	60-66	23	216-222	43	336-342
4	66-72	24	222-234	44	342-348
5	76-82	…	…	…	…
6	82-88				
7	174-180				
8	180-186				
9	186-192				
10	192-198				
11	198-204				
12	204-210				
13	210-216				
FM	88-108				
14	120-126				
15	126-132				
16	…				
…	…				

Frequency-Division Multiplexing – Example 2: Voiceband Signals

- $m_1(t)$: voiceband signal – bandwidth = 4000 Hz
- When modulated by a carrier f_1 = 64 KHz ➔ two identical sidebands; overall bandwidth = 2X4KHz = 8 KHz
- Information of $m_1(t)$ is preserved if one of the sidebands is eliminated (filtered out) ➔ bandwidth of modulated signal = 4 KHz
- (c) shows spectrum for composite signal using three subcarriers



(c) Spectrum of composite signal using subcarriers at 64 kHz, 68 kHz, and 72 kHz

Frequency-Division Multiplexing – Example 2: Voiceband Signals (2)

- Animation of FDM concept for voice calls

Frequency-Division Multiplexing – Analog Carrier Systems

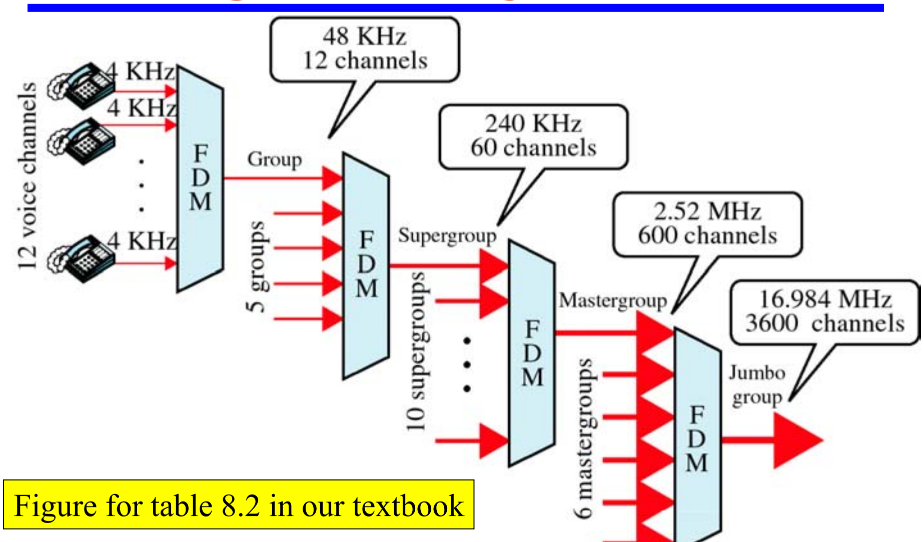
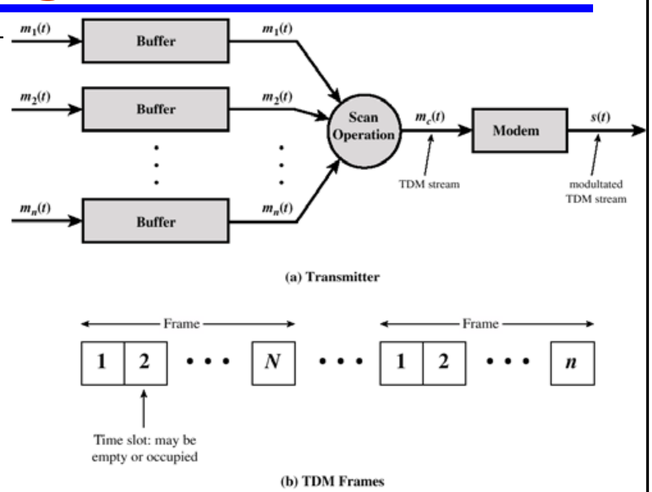


Figure for table 8.2 in our textbook

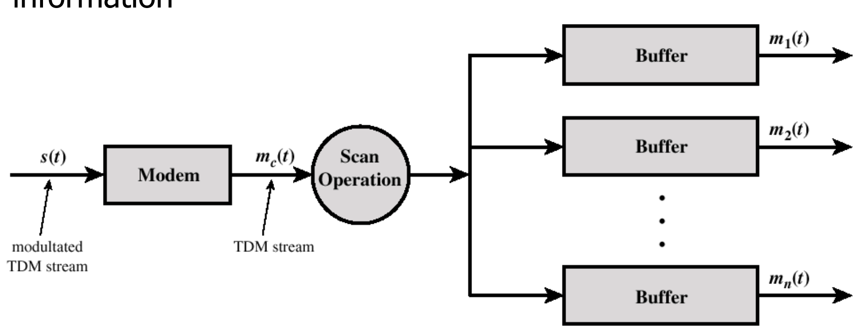
Synchronous Time-Division Multiplexing - Transmitter

- Digital sources $m_i(t)$ – usually buffered
- A scanner samples sources in a cyclic manner to form a frame
- $m_c(t)$ is the TDM stream or frame ➔ frame structure is fixed
- Frame $m_c(t)$ is then transmitted using a modem ➔ resulting analog signal is s(t)



Synchronous Time-Division Multiplexing - Receiver

- TDM signal s(t) is demodulated ➔ result is TDM digital frame $m_c(t)$
- $m_c(t)$ is then scanned into n parallel buffers;
- The i^{th} buffer correspond to the original $m_i(t)$ digital information



Synchronous Time-Division Multiplexing

- Animation of Synchronous TDM concept

Synchronous Time-Division Multiplexing – Bit/Character Interleaving

- TDM frame: sequence of slots – fixed structure – NOTE: no header/error control for this frame
  - One or more slots per digital source
  - The order of the slots dictated by the scanner control
  - The slot length equals the transmitter buffer length:
    - Bit: bit interleaving
      - Used for synchronous sources – but can be used for asynchronous sources
    - Character: character-interleaving
      - Used for asynchronous sources
      - Start/stop bits removed at tx-er and re-inserted at rx-er
- Synchronous TDM: time slots are pre-assigned to sources and FIXED
  - If there is data, the slot is occupied
  - If there is no data, the slot is left unoccupied

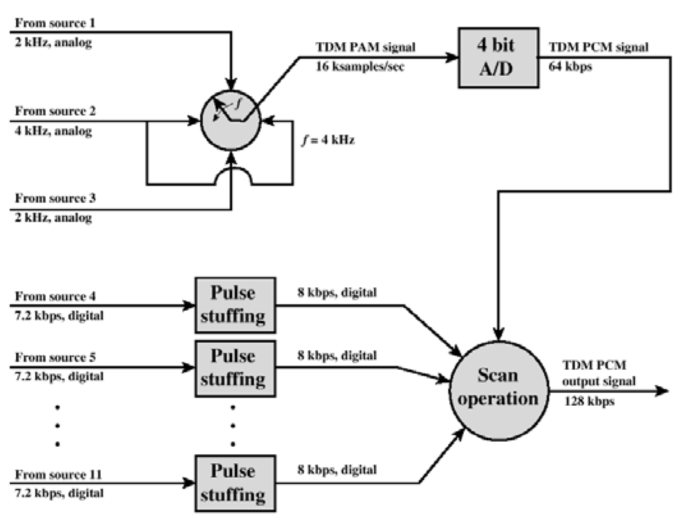
This is a cause of inefficiency!

TDM Link Control

- TDM frame:
  - No header and no error detection/control – these are per connection procedures
  - Frame synchronization is required – to identify beginning and end of frame
    - Added-digit framing: One control bit is added to each start of frame – all these bits from consecutive frame form an identifiable pattern (e.g. 1010101…)
    - These added bits for framing are inserted by system ➔ control channel
    - Frame search mode: Rx-er parses incoming stream until it recognizes the pattern ➔ then TDM frame is known
- Pulse stuffing:
  - Different sources may have separate/different clocks
  - Source rates may not be related by a simple rational number
  - Solution: inflate lower source rates by inserting extra dummy bits or pulses to mach the locally generated clock speed

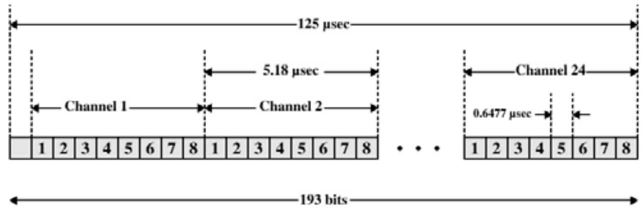
TDM – Example 1

- Step1: convert analog sources to digital using PCM
  - The ***sampling theorem*** determines the no of samples/sec
- The analog sources produce 16 sample/sec altogether ➔ 64 kb/s when converted to digital
- Note pulse stuffing is used to raise the 7.2 kb/s rate to 8 kb/s (a rational fraction of 64 kb/s) for digital sources



TDM – Example2: Digital Carrier Systems

- Voice call is PCM coded → 8 b/sample
- DS-0: PCM digitized voice call – R = 64 Kb/s
- Group 24 digitized voice calls into one frame as shown in figure →DS-1: 24 DS-0s
- Note channel 1 has all 1st bits from all of 24 calls; channel 2 has all 2nd bits from all 24 calls; etc.



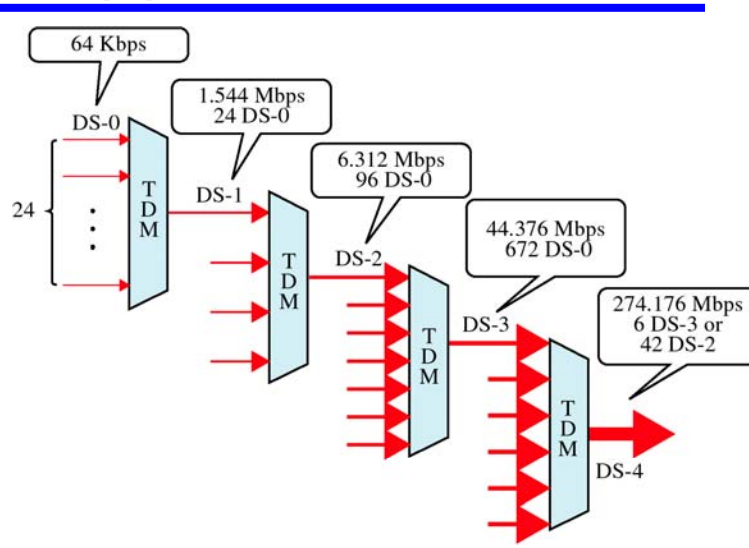
Notes:

1. The first bit is a framing bit, used for synchronization.
2. Voice channels:
   - •8-bit PCM used on five of six frames.
   - •7-bit PCM used on every sixth frame; bit 8 of each channel is a signaling bit.
3. Data channels:
   - •Channel 24 is used for signaling only in some schemes.
   - •Bits 1-7 used for 56 kbps service
   - •Bits 2-7 used for 9.6, 4.8, and 2.4 kbps service.

Figure 8.9 DS-1 Transmission Format

TDM – Example2: Digital Carrier Systems (2)

- TDM



Example: Problem 8-8

- **8-8: In the DS-1 format, what is the control signal data rate for each voice channel?**

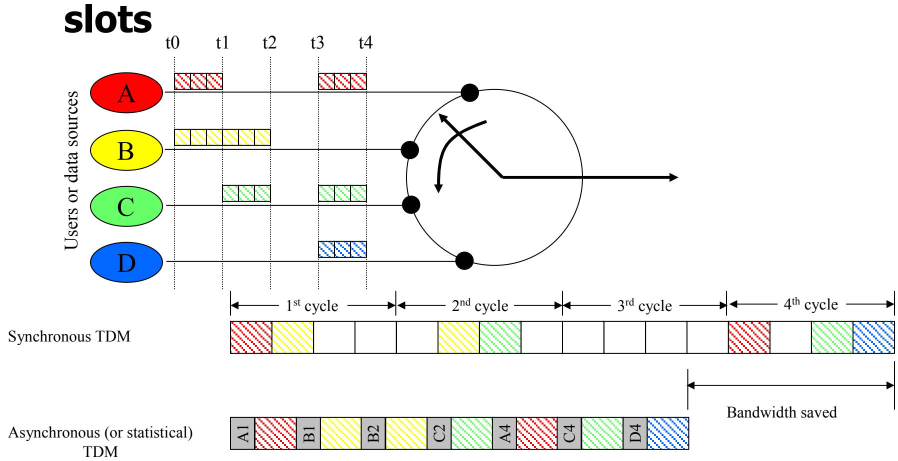
Solution:

There is one control bit per channel per six frames. Each frame lasts 125 μsec. Thus:

$$\text{Data Rate} = 1/(6 \times 125 \times 10^{-6}) = 1.33 \text{ kbps}$$

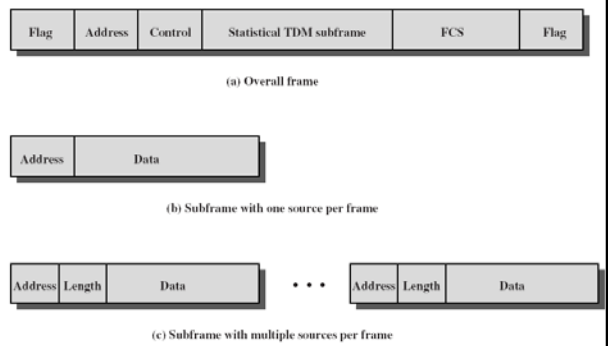
Statistical Time-Division Multiplexing

- **Dynamic and on-demand allocation of time slots**



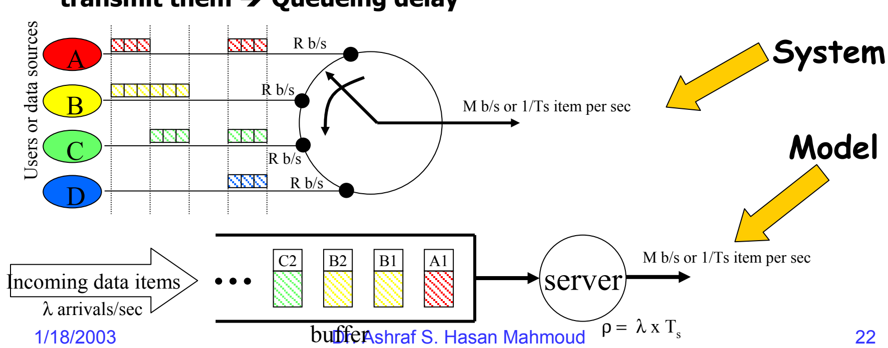
Statistical Time-Division Multiplexing Frame Format

- Clearly, the aim of statistical TDM is increase efficiency by not sending empty slots
- But it requires overhead info to work:
  - Address field
  - Length field



Statistical Time-Division Multiplexing – Modeling

- Data items (bits, bytes, etc) are generated at any time – source may be intermittent (bursty) not constant
- R b/s is the peak rate for single source
  - αR b/s is the average rate for single source ($0 \leq a \leq 1$)
- The *effective* multiplexing line rate is M b/s
- Each data item requires T_s sec to be served or tx-ed
- Data items may accumulate in buffer before server is able to transmit them → Queueing delay



Statistical Time-Division Multiplexing - Performance

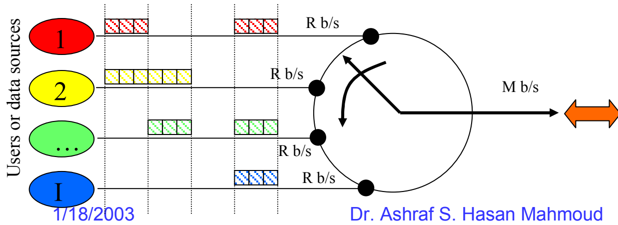
- Let I – number of sources

  R – data rate for each source

  M – effective capacity of multiplexed line

  α – mean fraction of time each source is transmitting

  K = M/(IR) – ratio of multiplexed line capacity total maximum input



Aggregate input (load or λ) = αIR
Capacity (service) = $M = 1/T_s$
Traffic Intensity, $\rho = \lambda T_s = \lambda/M$
$= \alpha IR/M$
$= \alpha/K$
For stable system $0 \le \rho < 1$

Statistical Time-Division Multiplexing – Performance (2)

- **Notes:**
  - K is a measure of compression achieved on the multiplexed line
  - α < K < 1:
    - K = 1 for synchronous TDM
    - If K < α (or ρ > 1) ➔ input is greater the line capacity (NOT STABLE)
  - ρ is measure of the load: for example, if M = 50kb/s and r = 0.25, then system load is ρM = 12.5 kb/s

- <u>Queueing Model Perspective</u>:

  λ: average number of arrivals per time unit

  T_s: average time to serve an arrival

  ρ: traffic intensity = λT_s

Aggregate input (load or λ) = αIR
Capacity (service) = $M = 1/T_s$
Traffic Intensity, $\rho = \lambda T_s = \lambda/M$
$= \alpha IR/M$
$= \alpha/K$
For stable system $0 \le \rho < 1$

Statistical Time-Division Multiplexing – Performance (3)

- (Refer to Queueing Model slide)
- Mean number of items in system (waiting & being served), N is given by:

$$N = \frac{\rho^2}{2(1-\rho)} + \rho$$

- Mean residence time (waiting and service), T_r is equal to

$$T_r = N / \lambda$$

Statistical TDM – Performance – Example

- 5 terminals are statistically multiplexed on 38.4 kb/s modem line; Each of the terminals transmits at a rate R = 9.6 kb/s 25% of the time. For each transmitted 5 bytes of user data (the data item), the asynchronous TDM frame contains 1 byte for address filed and 1 byte for length field.

a) What is the average number of data items in the system?

b) How many terminals we can connect to this system before the average delay exceeds 100 msec?

Statistical TDM – Performance – Example - Solution

a) I = 5 terminals; R = 9.6 kb/s; α = 0.25;
M = 38.4 kb/s – note for every 5 bytes of data the link transmits 7 bytes ➔ Effective M = (5/7) * 38.4 = 27.4 kb/s

$\lambda = \alpha IR$ = 12 kb/s, and $\rho = \lambda/M$ = 0.4374
$N = \rho^2/(2(1-\rho)+\rho$ = 0.6076 data item
$T_r = N/\lambda$ = 0.051 second

b) What is maximum I such that $T_r \leq 0.1$ sec using the above values for R, α, and Effective M and allowing I to vary from 5, 6, ..,11*

For I = 8, T_r = 0.079 sec
For I = 9, T_r = 0.104 sec
Therefore the maximum no of terminal to connect without making T_r exceed 100 msec is I = 8

*note that 11 is the maximum possible value for I regardless of T_r – this is because ρ should always remain ≤ 1, but $\rho = \alpha IR/M \leq 1$; which means $I \leq M/(\alpha R) = 11.4$; therefore the maximum number of terminals without consideration for T_r can be 11

Statistical Time-Division Multiplexing

- Animation of Asynchronous TDM concept

Example: Problem 8-13

- **8-13: Ten 9.6 kb/s lines are to be multiplexed using TDM. Ignoring overhead bits, what is the total capacity required for synchronous TDM? Assuming that we wish to limit the average multiplexed line utilization to 0.8, and assuming that each line is busy 50% of the time, what is the capacity required for statistical TDM?**

Example: Problem 8-13 - solution

Synchronous TDM: M = IR;

R = 9.6kb/s, I = 10 → M = ?

M = 9600 bps $\times$ 10 = 96 kbps

Statistical TDM:

Remember that $\rho = \alpha IR/M$;

ρ = 0.8, α = 0.5, R = 9.6kb/s, I = 10 → M = ?

M = 9600 bps $\times$ 10 $\times$ 0.5/0.8 = 60 kbps

Problems of INTEREST

- Problem List: 8-9, 8-10, 8-11, 8-12, 8-13, and 8-18
- Example on slide 25