Description of ResE Video Applications and Requirements

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IEEE 802.3 ResE SG
2005.05.16

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Outline

- ❑Introduction
- ❑Overview of video transport
- ❑Video - background
- ❑Properties of analog video signals
- ❑Properties of digital video signals
- ❑MPEG-2 transport of digital video
- ❑MPEG-2 transport across a network
- ❑Backup
  - ▪More detailed version of presentation
  - ▪References

Introduction

- This is the first of three related VG presentations
  1) Description of ResE Video Applications and Requirements
  2) Description of ResE Audio Applications and Requirements
  3) Jitter and Wander Requirements for ResE Applications

- The backup slides contain a more detailed version of the presentation
- For convenience, each presentation contains the complete (i.e., combined) reference list for all three presentations, at the end of the backup slides

Overview of Video Transport

- Analog video is digitally encoded
  - The source encoding is often a high bit rate, uncompressed format
  - There may be digital processing at the source
- Digitally encoded video is compressed
  - MPEG-2
  - MPEG-4
- Compressed video is transported from the source to the customer via one or more service providers
- At the residence, the compressed video will traverse ResE
  - ResE network is the final network, following one or more service provider networks
- In a DVD/local server application, the video originates as MPEG-2 at a DVD player in the residence and traverses ResE
  - In this case the video traverses only the ResE
    - No service provider network
- These scenarios will be illustrated in later slides

Analog Video - Background

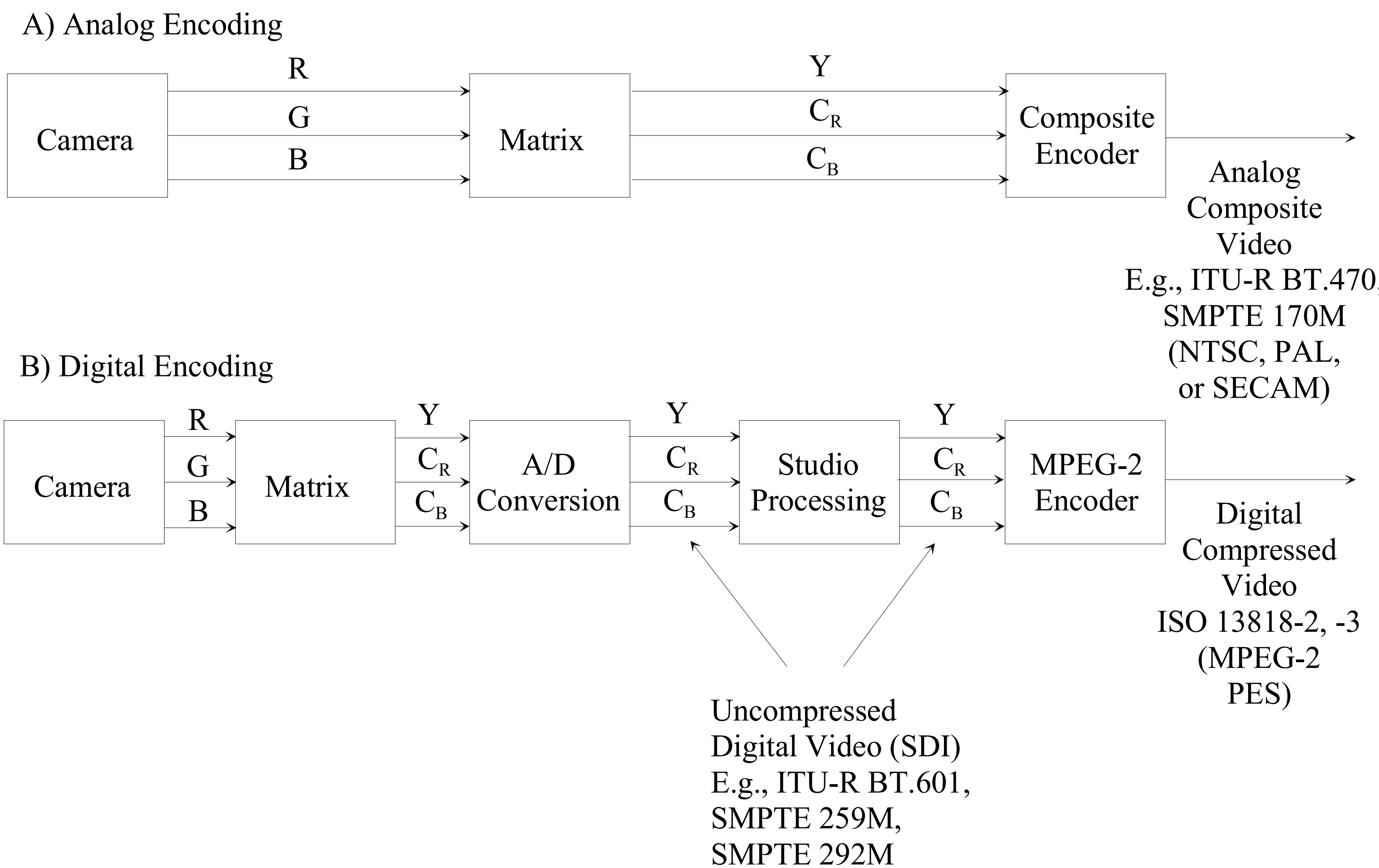
- Two main classes of video systems in use
  - ≈ 30 frames/s (actually 30/1.001 frames/s), 525 lines/frame
    - NTSC (ITU-R BT.470 and SMPTE 170M)
  - 25 frames/s, 625 lines/frame
    - PAL, SECAM (a number of varieties of each) (ITU-R BT.470)
  - Each frame consists of 2 interlaced fields, with 525/2 or 625/2 lines per field
- Video signal actually consists of 3 signals
  - Luminance signal (intensity)
  - 2 chrominance signals (color information)
- May transport the 3 components separately (component video)
- May combine the 3 signals into a single analog signal (composite video)
  - NTSC, PAL, SECAM are composite video formats
- Properties/requirements for signals are given in table in backup slides
  - Included in this are requirements for chroma subcarrier: nominal frequency, frequency offset, frequency drift
  - Properties are different for the three formats

Digital Video - Background

- Two classes of digital encodings of the analog video signals described above
  - Directly sample the composite video signal
  - Sample the 3 components of the component video signals and combine into one digital signal
- Sampled NTSC (143 Mbit/s) and PAL (177 Mbit/s) composite video signals are described in [7] (Serial Digital Interface (SDI))
- Sampled component video signals are described in [7] (serial digital interface) and [8] (both SDI and parallel digital interface)
  - 270 Mbit/s, 360 Mbit/s
- Sampled HDTV component video signals described in [9] (serial digital interface)
  - 1.485, 1.485/1.001 Gbit/s
- Jitter and wander requirements for SDTV
  - 0.2 UIpp for both timing (10 Hz high-pass) and alignment jitter (1 kHz high-pass)
  - Frequency offset and drift requirements same as for analog signals
- Jitter and wander requirements for HDTV
  - 1.0 UIpp (timing jitter, 10 Hz high-pass); 0.2 UIpp (alignment jitter, 100 kHz high-pass); frequency tolerance = ±10 ppm; no frequency drift requirement

MPEG-2 Transport of Digital Video

- The figure below, taken from [16], compares analog and digital video encoding
  - Part (b) shows that the input to the MPEG coder can be the SDI digital video signal

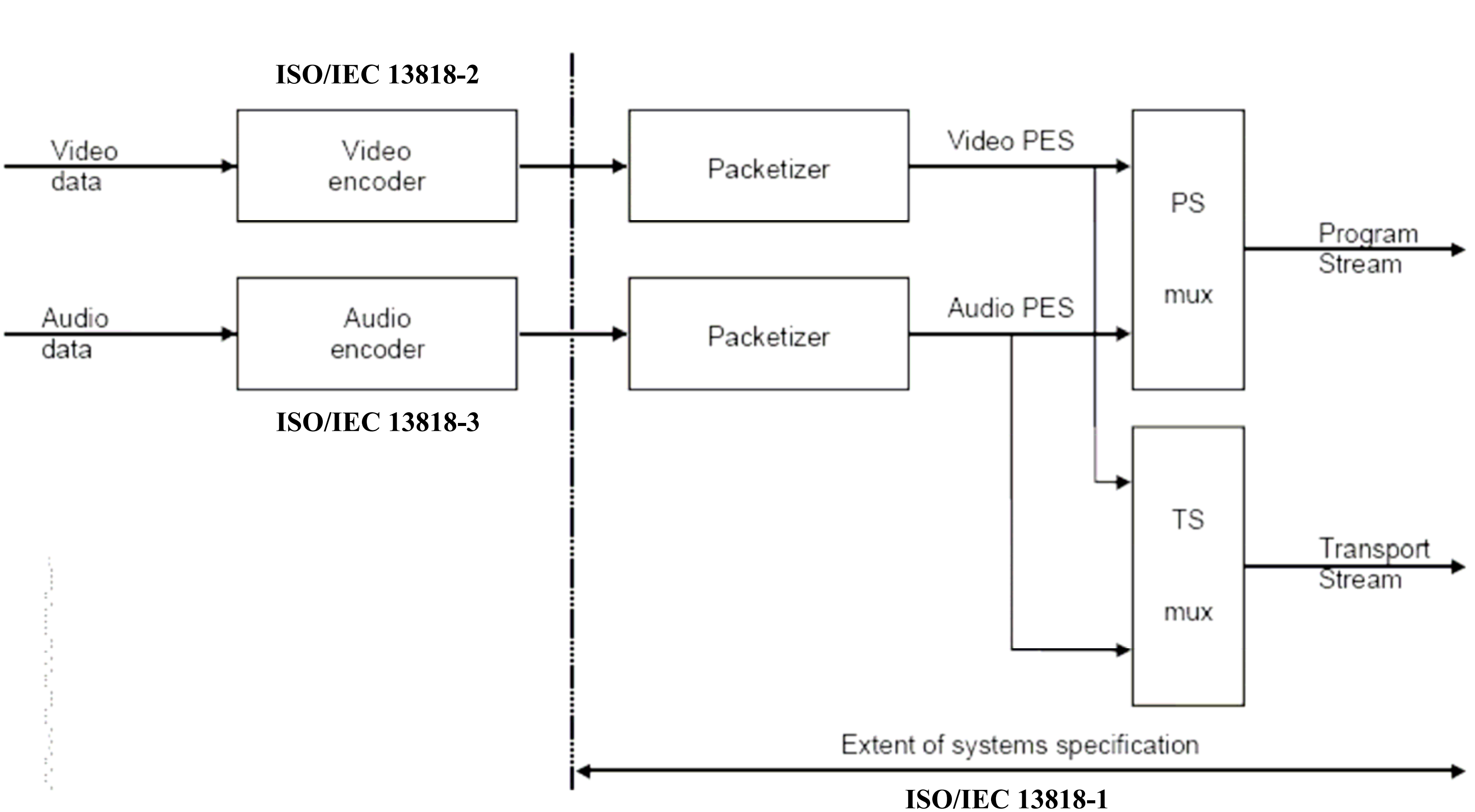


MPEG-2 Transport of Digital Video (Cont.)

- The compressed video and audio are packetized
  - Each such stream (video or audio) obtained from a single source (program) is a Packetized Elementary Stream (PES)
- The video and audio PESs for a program may be multiplexed, along with system information, into a Program Stream (PS)
  - Multiple PES packets are combined into PS Pack
    - Pack contains pack header, followed by system header, followed by PES packets
  - All the information in a PS is traceable to the same clock (because the original digitization of the video and audio of the program were done by the same clock)
- Multiple programs may be multiplexed, along with system information and information about the programs, into a Transport Stream (TS)
  - Each PES packet is mapped into one or more TS packets
    - TS packet size = 188 bytes
    - Last TS packet that contains information from a PES packet is padded to 188 bytes; a new PES packet begins a new TS packet
    - Each TS packet has a header
  - Each program in a TS may be traceable to a different clock; the multiplexing process includes a rate adjustment to the TS Reference Clock (see slides 18 and 19)
- TS packets tend to be much shorter than PS packs

MPEG-2 Transport of Digital Video (Cont.)

- Schematic of MPEG-2 encoding, packetization, multiplexing, and transport (taken from [15], with minor additions)



MPEG-2 Transport of Digital Video (Cont.)

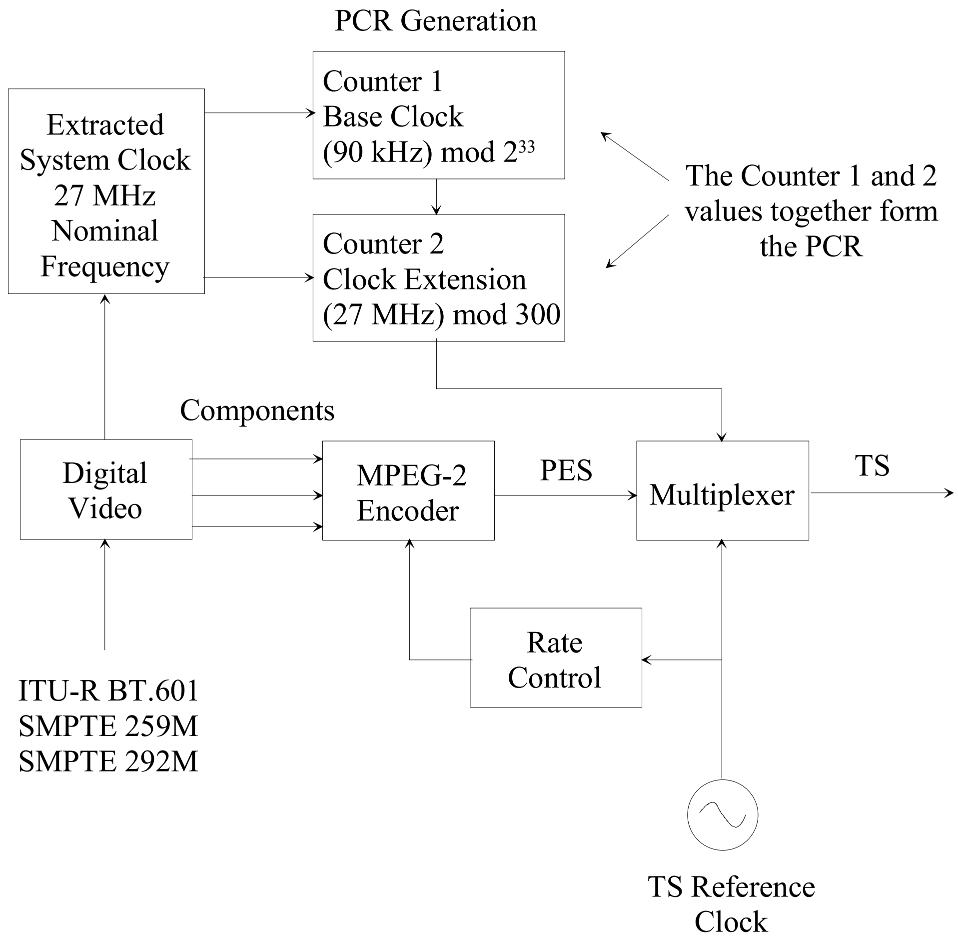
- Compression algorithm may result in the need to decode the PES packets at the receiver out of order
  - This occurs because some compression is achieved by predictive coding
    - A picture may depend on a previous picture, and also on a future picture
      - This scheme takes advantage of the fact that a scene may not change rapidly on the timescale of one frame
    - Note that if the frames are transmitted in the order in which they are encoded, they are transmitted out of order
  - As a result, decoding time may be different from presentation time
  - Each PES packet carries 2 time stamps (TS)
    - Decoding time stamp (DTS) – indicates when the packet should be decoded so that the information is available when needed for presentation at the video receiver
    - Presentation time stamp (PTS) – indicates when the information should be presented at the receiver
    - If the decoding and presentation times are the same, only one TS is sent
  - The DTS and PTS are obtained from values of a local, 90 kHz clock at the encoder
    - Traceable to the 27 MHz System Clock (described below) and referenced to this clock
    - May be obtained by dividing that clock by 300
    - The 90 kHz clock causes a counter to continuously increment, at this rate
    - Value of the counter at the desired time is encoded in a 33-bit TS

MPEG-2 Transport of Digital Video (Cont.)

- Compression algorithm may result in the need to decode the PES packets at the receiver out of order (Cont.)
  - Value of DTS/PTS at receiver indicates time, in units of the 90 kHz counter, that the packet data is to be decoded/presented
    - Therefore, need a clock at the receiver that is synchronized with the System Clock at the encoder
- The System Clock is traceable to the video source clock
  - There is a separate System Clock for each program in a transport stream

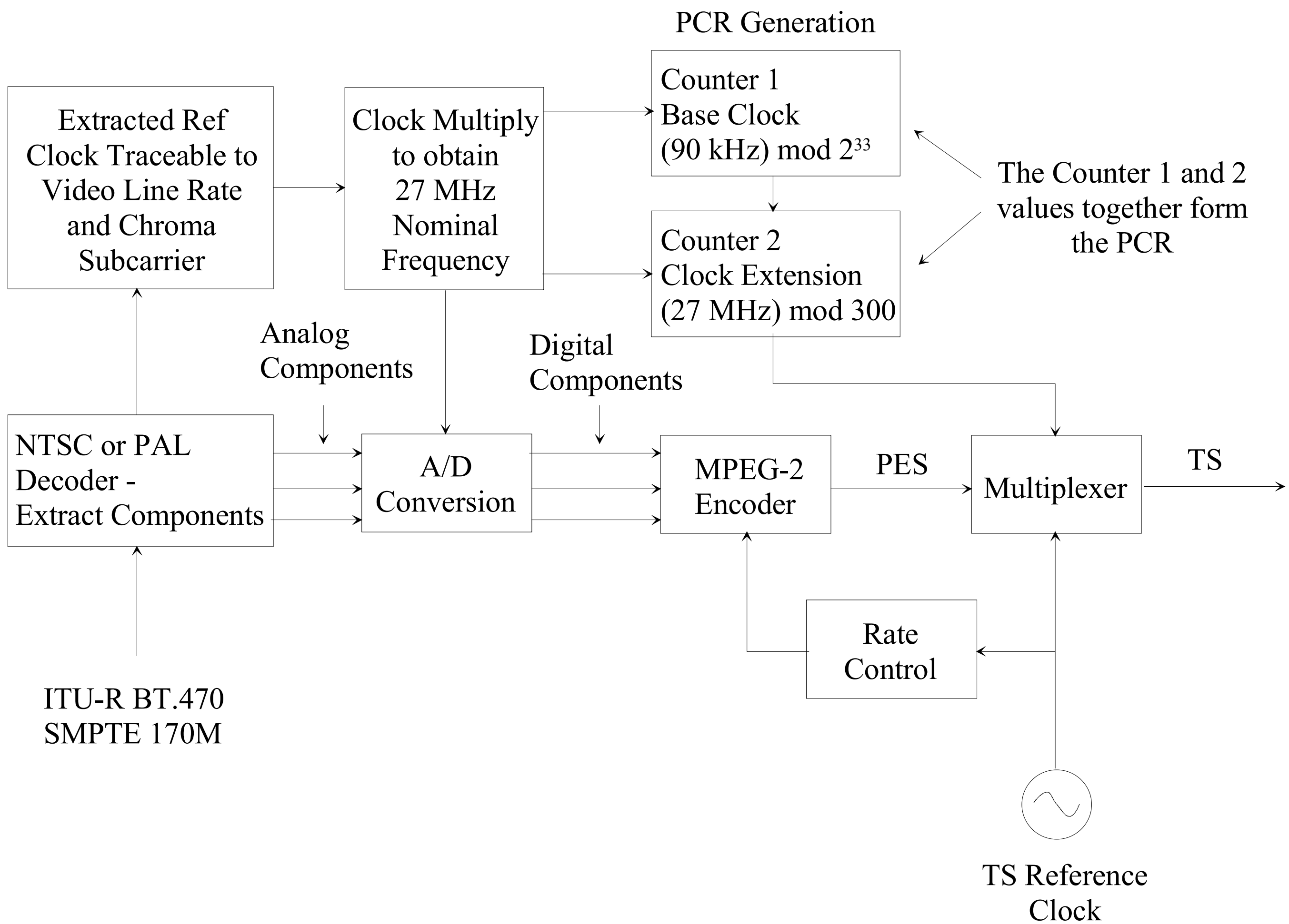
MPEG-2 Transport of Digital Video (Cont.)

- Illustration of generation of PCR values and adjustment of rate of mapping packets into TS to match TS rate (Figure adapted from similar figure in [32]) – digitized component video input



MPEG-2 Transport of Digital Video (Cont.)

- Illustration of generation of PCR values and adjustment of rate of mapping packets into TS to match TS rate (Figure adapted from similar figure in [32]) – analog composite video input

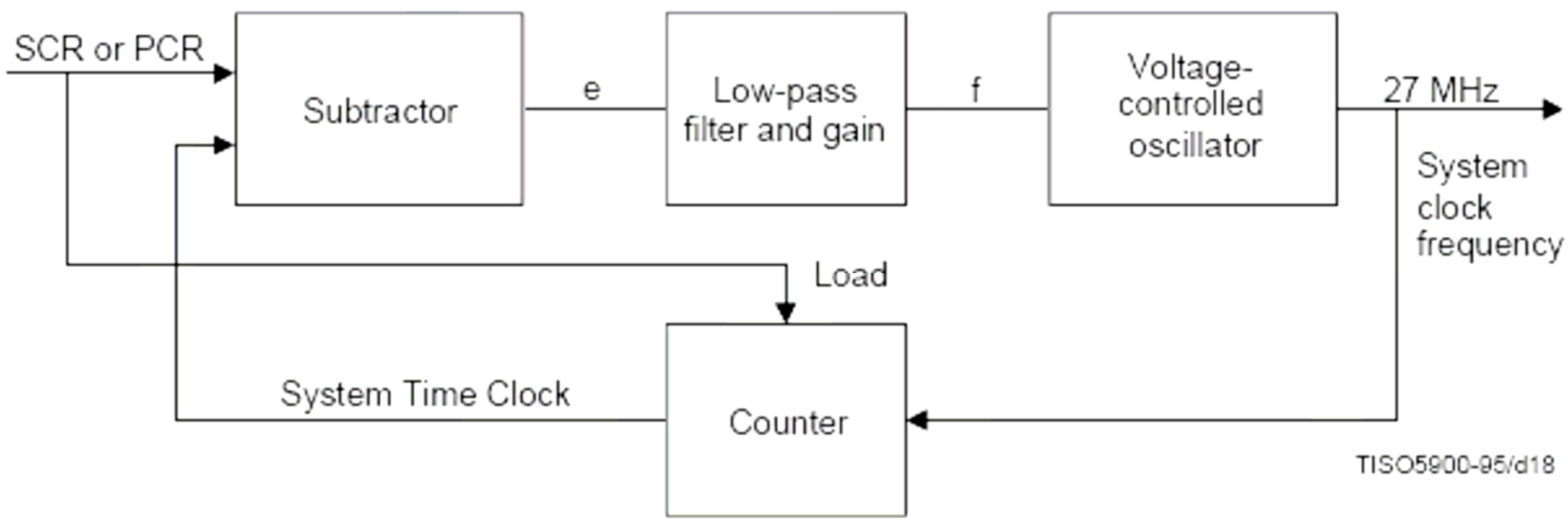


MPEG-2 Transport of Digital Video (Cont.)

- Since the System Clock and associated PCR values are traceable to the source video, they will reflect any jitter and wander present on this source
- However, additional jitter and wander will be added by the MPEG-2 multiplex/demultiplex process and by the transport network (e.g., ResE)
  - The use of PCR time stamps assumes that once a PCR value is obtained at the transmitter, the delay in transporting that value to the receiver is constant
  - Any variation in that delay will show up as added jitter/wander
- Sources of jitter/wander
  - Jitter/wander present on original digital video signal at source
  - Granularity of the 27 MHz clock (approximately 37 ns)
  - Delay variation caused by multiplexing or re-multiplexing of programs within a TS (rate matching, delay due to TS packets of different programs arriving simultaneously, etc.)
    - MPEG-2 will adjust PCR values to account for this, but [15] (section 2.4.2.2) allows up to 500 ns of phase error
  - Delay variation in transport network
    - Causes PCR/SCR/ESCR time stamps to arrive at times offset from the times reflected by the time stamp values
  - Jitter/wander generation in PLLs used to smooth above sources of jitter/wander

MPEG-2 Transport of Digital Video (Cont.)

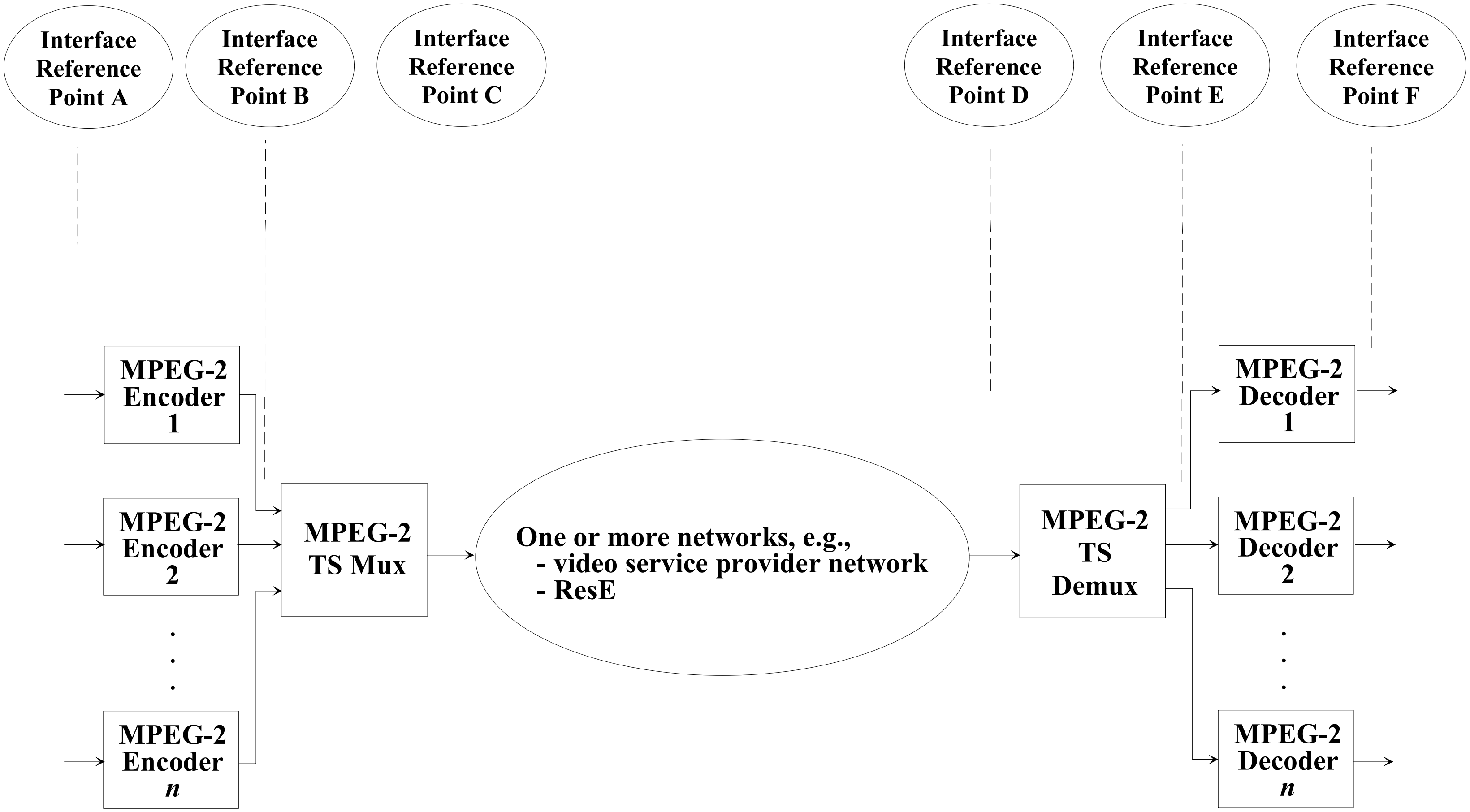
- Schematic of PCR/SCR/ESCR clock recovery PLL (taken from Annex D of [15])
  - Initial value of SCR/PCR/ESCR is loaded into counter to eliminate any initial phase offset



MPEG-2 Transport of Digital Video (Cont.)

- Jitter and wander requirements for MPEG-2
  - Formal requirements are in [15], but see [32] and [34] for good discussions
  - These specify the amount of jitter and wander the MPEG decoder is required to cope with
    - If the requirements were exceeded, the decoded video could contain impairments
- Maximum phase offset in received PCR timestamps
  - $\pm$ 500 ns (section 2.4.2.2 of [15])
    - Includes PCR phase offset due to System clock granularity and multiplexing/re-multiplexing of program
    - **Does not include PCR phase offset due to network-induced jitter**
  - Maximum phase offset for case where the packets traverse one or more networks is specified in [38]
    - $\pm$ 25 μs (section 3.5 of [38])
- Maximum frequency offset implied by PCR timestamps
  - $\pm$ 810 Hz (section 2.4.2.1 of [15])
  - Equivalent to $\pm$ 30 ppm for 27 MHz nominal rate
- Maximum frequency drift rate
  - 75×10^{-3} Hz/s (section 2.4.2.1 of [15])
  - Equivalent to 0.000278 ppm/s for 27 MHz nominal rate

MPEG-2 Transport Across a Network



Reference Points A and F
- E.g., ITU-R BT.601,
SMPTE 259M
SMPTE 292M

Reference Points B and C
- ISO 13818-1;
ISO 13818-2 (Ref. Pt. B);
ISO 13818-3 (Ref. Pt. B)

Reference Points D and E
- ISO 13818-1;
ISO 13883-9;
ISO 13818-2 (Ref. Pt. B)
ISO 13818-3 (Ref. Pt. B)

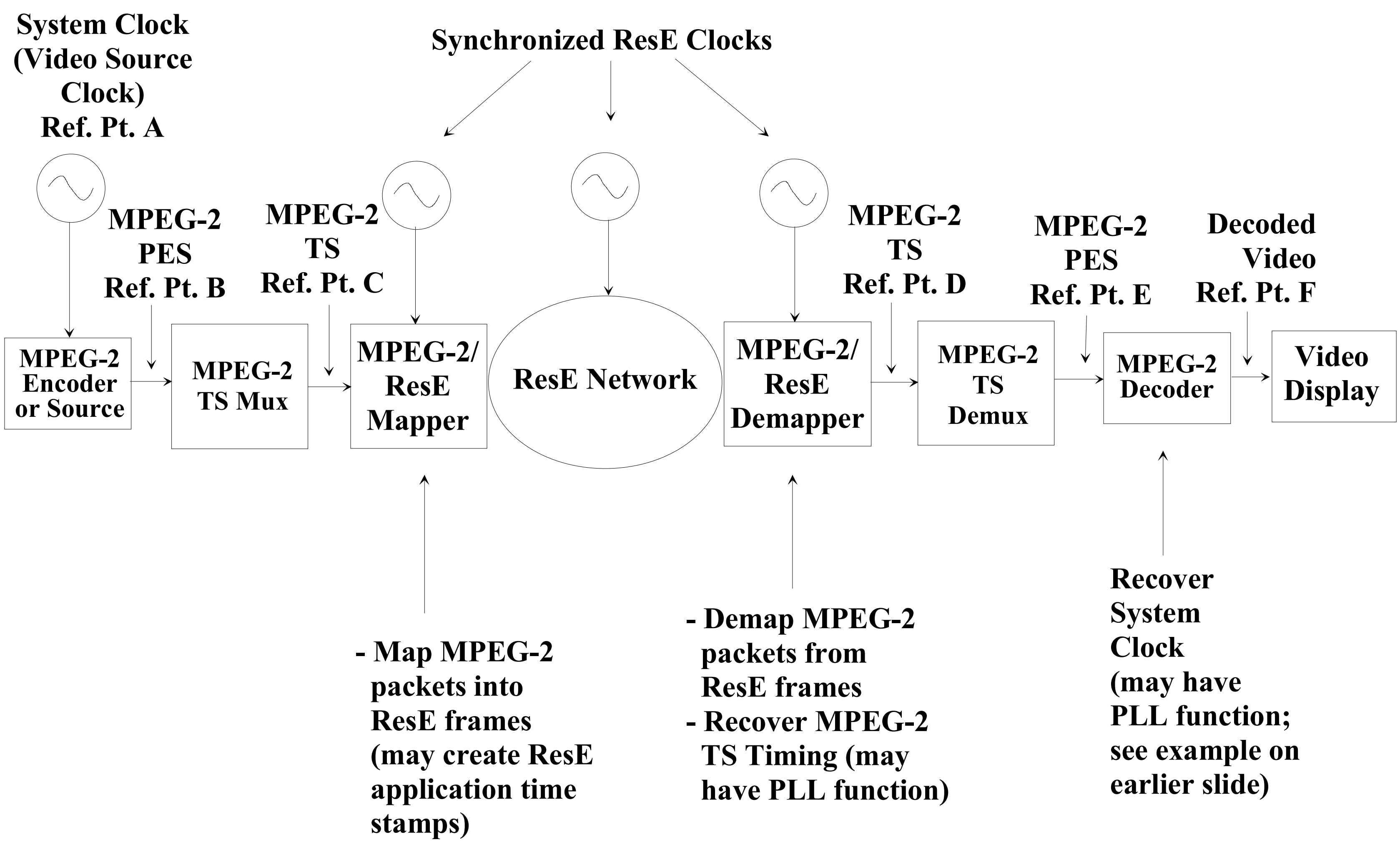
- Figure adapted from p.10 of [38]

MPEG-2 Transport Across a Network (Cont.)

- Transport of MPEG-2 across a network may involve various scenarios
  - Single ResE network (and no other network transport)
    - E.g., video originates in residence at DVD player, local server, or camcorder
      - Video is transported over ResE and displayed on TV
        - MPEG-2 decoder function may be integrated in TV or exist in a separate unit (e.g., set-top box)
  - Transport across one or more video service provider networks to residence, followed by transport across ResE
    - E.g., video originates in studio of content provider
    - Video either originates in digital form (previously encoded and stored) or A/D conversion occurs in studio
    - Digital video is transported from studio across one or more content provider/service provider networks
      - MPEG-2 encoding may occur at source, or digital video may be initially transported as SDI signal (uncompressed) and MPEG-2 encoding occurs at intermediate point
    - MPEG-2 video is delivered to residence
    - MPEG-2 video is transported across ResE to TV
      - MPEG-2 decoder function may be integrated in TV or exist in a separate unit (e.g., set-top box)

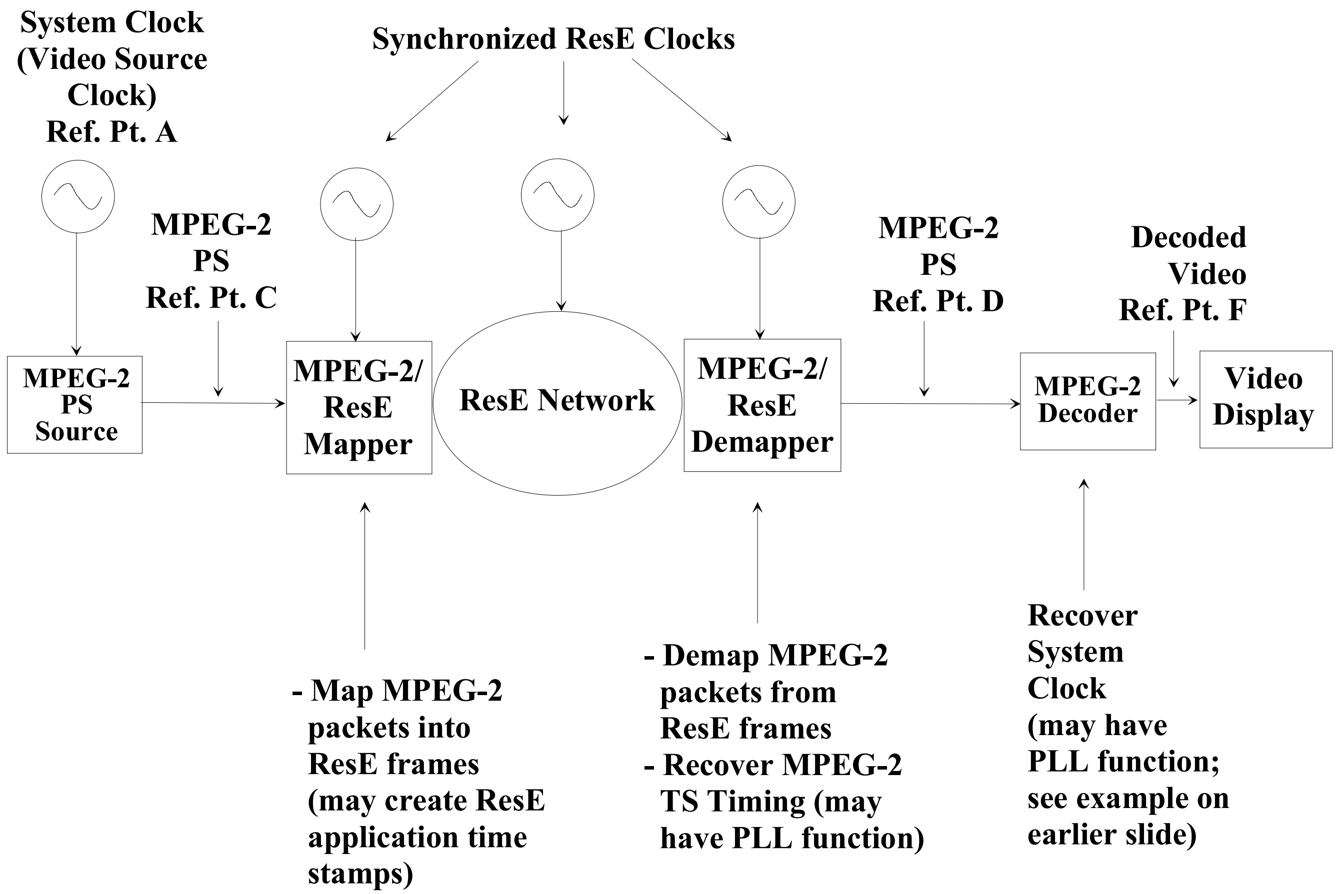
MPEG-2 Transport Across a Network (Cont.)

- Transport across a single ResE network (and no other network)



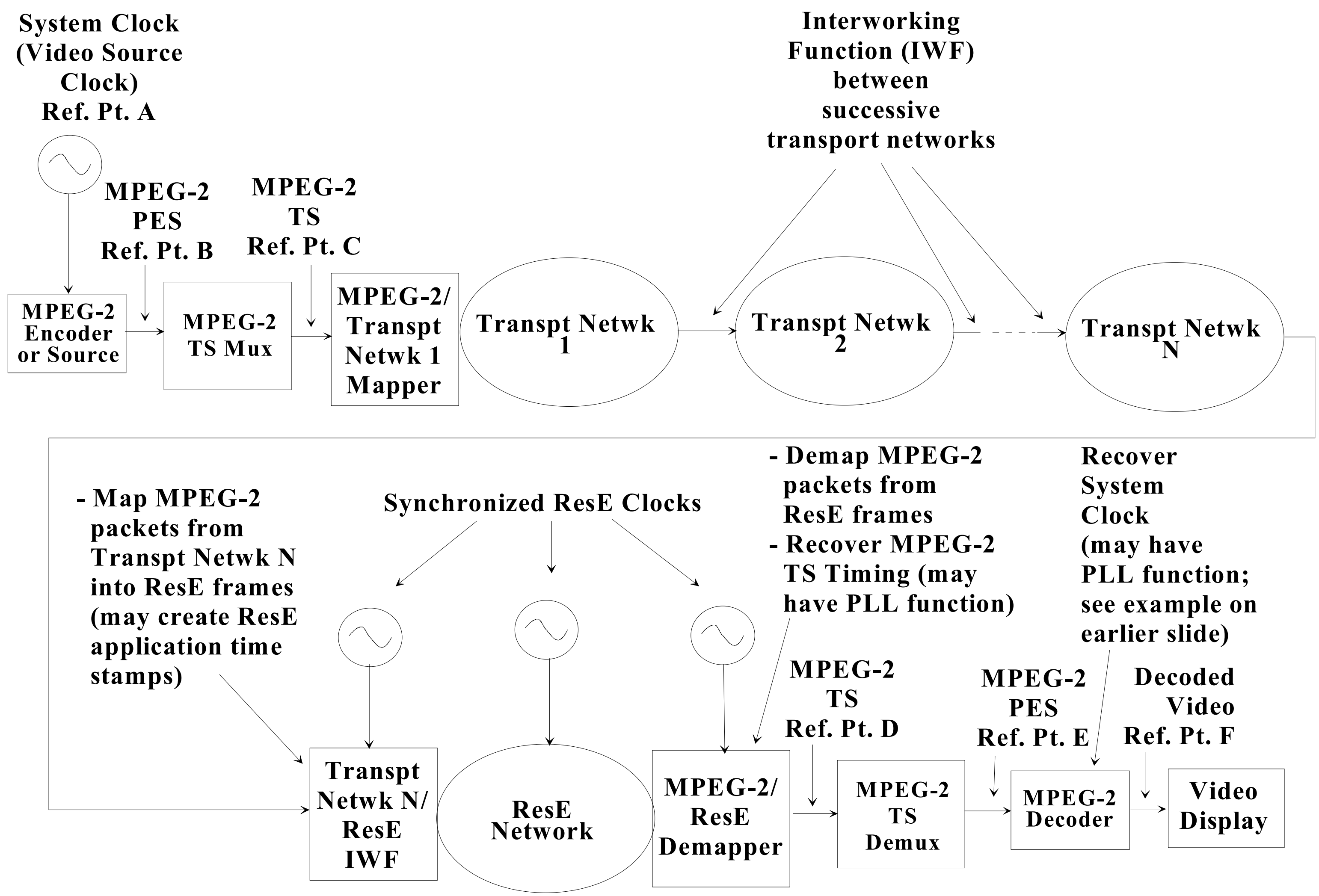
MPEG-2 Transport Across a Network (Cont.)

- Transport of PS across a single ResE network (and no other network) for the case where the video is already digitized as a PS and stored locally (e.g., in a DVD)



MPEG-2 Transport Across a Network (Cont.)

- Transport across one or more video service provider networks to residence, followed by transport across ResE



MPEG-2 Transport Across a Network (Cont.)

- Peak-to-peak phase variation, frequency offset, and frequency drift requirement at Reference Point D (MPEG-2/ResE Demapper) is for combined effect of transport across all the networks
  - To reiterate, the requirements are ±25 μs (peak-to-peak phase variation), ±30 ppm (frequency offset), and 0.000278 ppm/s (frequency drift rate)
- If there is only transport across ResE, then the ResE network may generate jitter and wander up to these requirements
- However, if a number of video service provider/content provider networks are present, the ResE network may only use a budgeted allocation
- Problem: we need to know how much of the above peak-to-peak phase variation, frequency offset, and frequency drift requirements can be allocated to ResE
  - i.e, jitter/wander budgets are needed
- ISO 13818-1 and ITU-T H.222 are developed by ISO JTC1/SC29 and by ITU-T SG 16, Q 6
  - Question: Have these groups (or any other group) budgeted jitter and wander to various networks for the case where MPEG-2 is transported across multiple service/content provider networks?
    - If they have not, then how is is ensured that accumulated jitter and wander across a number of transport networks is within limits?

MPEG-2 Transport Across a Network (Cont.)

- Note that from the perspective of ResE, the precise manner in which peak-to-peak phase variation, frequency offset, and frequency drift are budgeted is not important
  - ResE cares mainly about the budget components it gets
  - ResE does not care how the remaining portion is budgeted among the other transport networks
  - ResE also does not care about the details of how the MPEG-2 packets are handed from one transport network to the next

Backup

More detailed version of presentation, plus references

Video - Background

- See [6] for a good introduction to analog and digital video
- Two main classes of video systems in use
  - 30 frames/s, 525 lines/frame
    - More precisely, rate is 30/1.001 frames/s (color) and 30 frames/s (black and white)
      - See Chapter 8 of [4] for background on the 1.001 factor
  - 25 frames/s, 625 lines/frame
  - Each frame consists of 2 interlaced fields, with 525/2 or 625/2 lines per field
    - This is unimportant for end-to-end performance requirements discussed here
- Video signal actually consists of 3 signals
  - Luminance signal (intensity)
  - 2 chrominance signals (color information)
  - Various color coordinate systems are defined, e.g.,
    - R, G, B (Red, Green, Blue)
    - Y (luminance), $C_R = R - Y$, $C_B = B - Y$ (color differences)
      - $Y = 0.587G + 0.114B + 0.299R$ (definition)
    - Y (luminance), I (in phase), Q (quadrature)
      - I and Q are defined as particular linear combinations of R, G, B, or, equivalently, of Y, C_R, and C_B
  - The specific color coordinate system used is not important here; what matters is that there are 1 luminance and 2 chrominance signals (or, for RGB, 3 color signals)

Video – Background (Cont.)

- ❑Each signal is a function of time
  - ▪Display the points (pixels) on each line successively (moving from left to right)
  - ▪Display the successive lines in a field, moving from top to bottom
  - ▪Display the successive fields in a frame
  - ▪Display the successive frames
- ❑Two classes of analog video interface to a display (e.g., TV)
  - ▪Composite video
    - •Combine the luminance and chrominance information into a single analog signal
    - •Chrominance information is transmitted by modulating a subcarrier of the main signal (the chroma subcarrier)
  - ▪Component video
    - •The video information is transmitted as 3 separate signals
      - –R, G, B
      - –Y, R-Y, B-Y
      - –Y, I, Q
      - –Etc.

Video – Background (Cont.)

- Standardized composite video signals
  - 30/1.001 frames/s, 525 lines/frame
    - NTSC
  - 25 frames/s, 625 lines/frame
    - PAL (various forms)
      - Referred to as M, B, B1, D, D1, G, H, K, N, and I/PAL
    - SECAM (various forms)
      - Referred to as B, D, G, H, K, K1, and L/SECAM
  - All the above are described in ITU-R BT.470-6, *Conventional Television Systems* [1]
  - NTSC is also described in SMPTE 170M-1999, *Composite Analog Video Signal – NTSC for Studio Applications* [2]
  - Additional information on composite video signals is given in [3] and [4]
- The following slides present properties of analog video signals, with emphasis on those properties needed here
  - This material is important because, in decoding digitally encoded video, the chroma subcarrier frequency is traceable to the recovered clock at the decoder
    - Therefore, requirements on chroma subcarrier frequency place requirements on digital video clock recovery
  - Information is taken from References [1] – [4]

Properties of Analog Video Signals (see [1]-[4])

Characteristic	NTSC	PAL	SECAM
Number of lines per picture (frame) N_P	525	625	625
Number of fields per frame	2	2	2
Number of lines per field N_L	262 ½	312 ½	312 ½
Nominal field frequency f_V (Hz)	$60/1.001 \approx 59.94$ (color) 60 (B&W)	50	50
Nominal frame frequency (Hz)	$30/1.001 \approx 29.97$ (color) 30 (B&W)	25	25
Nominal line frequency $f_H = N_L f_V$ (Hz)	$15750/1.001 = 2.25 \times 10^6/143 \approx 15734.27$ (color) 15750 (B&W)	15625	15625

Properties of Analog Video Signals (Cont.)

Characteristic	NTSC	PAL	SECAM
Nominal chroma subcarrier frequency f_{SC} (MHz) NTSC and PAL use suppressed carrier AM of 2 subcarriers in quadrature SECAM uses FM of 2 subcarriers for color differences	$\frac{455}{2} f_H \times 10^{-6} = \frac{315}{88} \approx 3.579545$	B, B1, D, D1, G, H, I, K,N/PAL $\left(\frac{1135}{4} f_H + \frac{1}{2} f_V\right) \times 10^{-6}$ $= \frac{17.734475}{4} = 4.43361875$ M/PAL $\frac{909}{4} f_H \times 10^{-6}$ $= \frac{14.203125}{4} = 3.55078125$ N/PAL (Argentina) $\left(\frac{917}{4} f_H + \frac{1}{2} f_V\right) \times 10^{-6}$ $= \frac{14.328225}{4} = 3.58205625$	For B-Y $f_{OB} = 272 f_H \times 10^{-6} = 4.25$ For R-Y $f_{OR} = 282 f_H \times 10^{-6} = 4.40625$
Chroma subcarrier frequency accuracy Δf_{SC} (Hz)	±10	±1 (I/PAL) ±5 (B, B1, D, D1, G, H, K,N/PAL)	±2000 (a note in [1] indicates that a reduction in tolerance is desirable)

Properties of Analog Video Signals (Cont.)

Characteristic	NTSC	PAL	SECAM
Chroma subcarrier frequency accuracy $y = \Delta f_{SC} / f_{SC}$ (ppm)	$\pm\frac{176}{63} \approx \pm 2.79365079$	B, B1, D, D1, G, H, K, N/PAL $\pm\frac{800000}{709379} \approx \pm 1.12774694$ I/PAL $\pm\frac{160000}{709379} \approx \pm 0.22554938897$ M/PAL $\pm\frac{1280}{909} \approx \pm 1.40814081$	For B-Y $\pm\frac{8000}{17} \approx \pm 470.58824$ For R-Y $\pm\frac{64000}{141} \approx \pm 453.90071$ (a note in [1] indicates that a reduction in tolerance is desirable)
Maximum chroma subcarrier frequency drift rate D_{SC} (Hz/s)	0.1	0.1	?? (Table on p.19 of [5] indicates no requirement for SECAM)

Properties of Analog Video Signals (Cont.)

Characteristic	NTSC	PAL	SECAM
Maximum chroma subcarrier frequency drift rate $D = D_{SC}/f_{SC}$ (ppm/s)	$\frac{44}{1575} \approx 0.027936508$	B, B1, D, D1, G, H, I, K,N/PAL $\frac{16000}{709379} \approx 0.022554938897$ M/PAL $\frac{128}{4545} \approx 0.02816281628$ N/PAL (Argentina) $\frac{16000}{573129} \approx 0.02791692621$	?? (Table on p.19 of [5] indicates no requirement for SECAM)

Properties of Digital Video Signals

- Two classes of digital encodings of the analog video signals described above
  - Directly sample the composite video signal
  - Sample the 3 components of the component video signals and combine into one digital signal
- Sampled NTSC and PAL composite video signals are described in [7] (Serial Digital Interface (SDI))
- Sampled component video signals are described in [7] (serial digital interface) and [8] (both SDI and parallel digital interface)
- Sampled HDTV component video signals described in [9] (serial digital interface)
  - note that HDTV signals are not described above)

Properties of Digital Video Signals (Cont.)

❑Sampled NTSC and PAL composite video signals [7]

- Sampling rate = $4f_{SC}$
- 10 bits/sample
- Therefore, nominal bit rate = $40f_{SC}$
    - NTSC nominal bit rate = (40)(315)/88 Mbits/s = 1575/11 Mbit/s = 143.1818 Mbit/s
    - PAL nominal bit rate = (40)(17.734475/4) Mbit/s = 177.34475 Mbit/s
        - Applies to B, B1, D, D1, G, H, I, K,N/PAL
        - [7] does not define a sampled PAL signal for MPAL or the version of NPAL used in Argentina
- Output jitter requirements (accumulated jitter at an equipment interface, i.e., network limit)
    - Timing (wide-band) jitter: 0.2 UIpp measured with 10 Hz high-pass filter
    - Alignment (high-band jitter): 0.2 UIpp measured with 1 kHz high-pass filter
    - While the current timing jitter requirement is the same as the alignment jitter requirement, Annex B of [7] indicates that purely digital systems can operate correctly with larger amounts of timing jitter and that SMPTE committees are evaluating the preferred value
        - In the digital domain, any jitter cleanup Phase-Locked Loop (PLL) must have a buffer sufficient to tolerate whatever level of jitter is present, given its bandwidth and gain peaking
- Output wander requirements (network limit)
    - Chroma subcarrier of recovered analog signal must meet the frequency offset and drift rate requirements given above
        - This means that the digital signal must meet these requirements, in ppm and ppm/s

Properties of Digital Video Signals (Cont.)

❑Sampled NTSC and PAL composite video signals (cont.)

- Output wander requirements (cont.)
  - Requirements are also given in [10], referenced to chroma subcarrier
    - Chroma subcarrier should be within ±1 Hz of nominal
      - [10] uses the most stringent of the NTSC and PAL requirements
    - Chroma subcarrier maximum drift rate of 0.1 Hz/s
  - Maximum frequency offset
    - NTSC: ±2.79365 ppm
    - PAL: ±0.225549 ppm (most stringent variety)
  - Maximum frequency drift rate
    - NTSC: 0.027937 ppm/s
    - PAL: 0.0225549 ppm/s (most stringent variety)
  - We will eventually use the most stringent of the requirements

Properties of Digital Video Signals (Cont.)

- Sampled component video signals ([7] and [8])
  - Two sampling rates are standardized
    - 13.5 MHz
    - 18 MHz
  - Number of samples per line for 13.5 MHz rate
    - NTSC: 858
    - PAL, SECAM: 864
    - Verify
      - NTSC $(858 \text{ samples/line})(\frac{15750}{1.001} \text{ lines/s}) = 13.5 \text{ MHz}$
      - PAL, SECAM $(864 \text{ samples/line})(15625 \text{ lines/s}) = 13.5 \text{ MHz}$
  - Number of samples per line for 18 MHz rate
    - NTSC: 1144
    - PAL, SECAM: 1152
    - Verify
      - NTSC $(1144 \text{ samples/line})(\frac{15750}{1.001} \text{ lines/s}) = 18 \text{ MHz}$
      - PAL, SECAM $(1152 \text{ samples/line})(15625 \text{ lines/s}) = 18 \text{ MHz}$
  - 10 bits/sample specified in [7]; 8 bits/sample, with 10 optional, in [8]

Properties of Digital Video Signals (Cont.)

- Sampled component video signals (cont.)
  - Luminance signal is sampled at the respective sampling rate
  - The 2 chrominance signals may be sampled at subrate
    - Chrominance signal may be decimated because the human eye sees color with less spatial resolution than black and white [6]
    - [6] summarizes a number of formats (with various amounts of decimation in sampling the chrominance signal)
    - 4:2:2 sampling [7], [8] – each chrominance signal is sampled at ½ the above bit rate
      - 4:2:2 notation means 4 luminance samples per set of 4 samples and, for each chrominance signal, 2 samples per set of 4 samples
      - Total bit rate for 13.5 MHz sampling is (13.5 MHz)(2)(10 bits/sample) = 270 Mbit/s
      - Total bit rate for 18 MHz sampling is (18 MHz)(2)(10 bits/sample) = 360 Mbit/s
    - 4:4:4 sampling standardized in [8] – each chrominance signal is sampled at the above bit rate
      - 4:4:4 notation means 4 luminance samples per set of 4 samples and, for each chrominance signal, 4 samples per set of 4 samples
      - For 10 bits/sample, bit rates are 405 Mbit/s (13.5 MHz sampling) and 540 Mbit/s (18 MHz sampling)

Properties of Digital Video Signals (Cont.)

- Sampled component video signals (cont.)
  - Output jitter requirements (accumulated jitter at an equipment interface, i.e., network limit)
  - Jitter requirements are the same as for sampled composite video [7]
    - Timing (wide-band) jitter: 0.2 UIpp measured with 10 Hz high-pass filter
    - Alignment (high-band jitter): 0.2 UIpp measured with 1 kHz high-pass filter
    - While the current timing jitter requirement is the same as the alignment jitter requirement, Annex B of [7] indicates that purely digital systems can operate correctly with larger amounts of timing jitter and that SMPTE committees are evaluating the preferred value
      - In the digital domain, any jitter cleanup Phase-Locked Loop (PLL) must have a buffer sufficient to tolerate whatever level of jitter is present, given its bandwidth and gain peaking
  - Output wander requirements (network limit)
    - Reference [10] indicates that component and composite video signals must meet the same wander requirements
    - Chroma subcarrier of recovered analog signal must meet the frequency offset and drift rate requirements given above
      - This means that the digital signal must meet these requirements, in ppm and ppm/s

Properties of Digital Video Signals (Cont.)

❑Sampled component video signals (cont.)

- Output wander requirements (cont.)
  - Requirements of [10] referenced to chroma subcarrier
    - Chroma subcarrier should be within ±1 Hz of nominal
      - » [10] uses the most stringent of the NTSC and PAL requirements
    - Chroma subcarrier maximum drift rate of 0.1 Hz/s
  - Maximum frequency offset that was given above for composite video
    - NTSC: ±2.79365 ppm
    - PAL: ±0.225549 ppm (most stringent variety)
  - Maximum frequency drift rate that was given above for composite video
    - NTSC: 0.027937 ppm/s
    - PAL: 0.0225549 ppm/s (most stringent variety)
  - We will eventually use the most stringent of the requirements

Properties of Digital Video Signals (Cont.)

- Sampled HDTV component video signals
  - Two standardized rates given in [9]
    - 1.485 Gbit/s
    - $1.485/1.001 \approx 1.484$ Gbit/s
- Details of sampling given in table on next slide (taken from [9], [11], [12])
  - For each rate, both interlaced and progressive scan formats are defined
  - Note that the sampling rates are based on the total numbers of lines per frame and samples per line
    - Numbers of active lines per frame and samples per active line are less
      - 1280×720 (corresponding to 1650×750 in table on next slide)
      - 1920×1080 (corresponding to 2376×1250 in table on next slide)
  - Nominal sampling rate obtained as
    - (Nominal frame rate)(total number of lines/frame)(total number of samples/line)
      - Total number of samples per line is combined luminance and chrominance

Properties of Digital Video Signals (Cont.)

Standard	SMPTE 296M-2001	SMPTE 296M-2001	SMPTE 295M-1997
Nominal frame rate (Hz)	60 or 30	60/1.001 or 30/1.001	50 or 25
Number of lines per picture (frame) N_P	750	750	1250
Number of fields per frame	1 or 2	1 or 2	1 or 2
Number of luminance samples per line	1650	1650	2376
Number of chrominance samples per line	1650	1650	2376
Total sampling rate (MHz)	148.5	148.5/1.001	148.5

Properties of Digital Video Signals (Cont.)

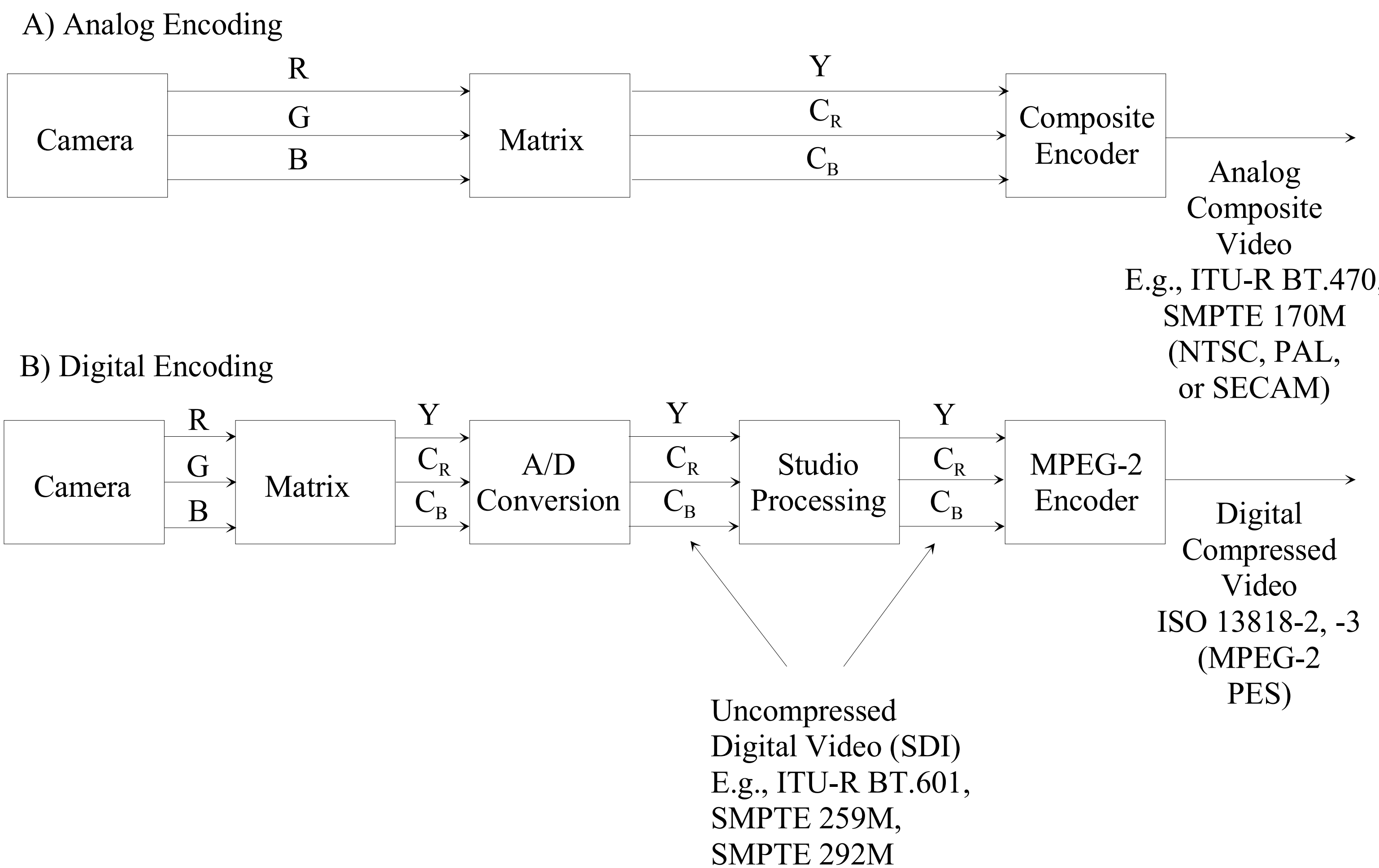
- Output jitter requirements (accumulated jitter at an equipment interface, i.e., network limit)
  - Timing (wide-band) jitter: 1.0 UIpp measured with 10 Hz high-pass filter
  - Alignment (high-band jitter): 0.2 UIpp measured with 100 kHz high-pass filter
  - Timing and alignment jitter limits are different (unlike standard definition TV jitter limits [7])
- Frequency accuracy requirement given in [11] and [12]
  - Maximum frequency offset: ±10 ppm
- No requirement on frequency drift rate

MPEG-2 Transport of Digital Video Signals

- MPEG-2 is a standard for compressing and transporting digitized video
  - The input is often one of the SDI signals described above
- MPEG-2 is standardized in ISO/IEC 13818 (parts 1 – 10)
  - Part 2 (Video) describes the encoding (including any compression) of already digitized video (e.g., SDI signals) [13]
    - Also contained in ITU-T Rec. H.262
  - Part 3 (Audio) describes the encoding (including any compression) of already digitized audio [14]
  - Part 1 (Systems) describes the packetization and transport of the compressed video and audio [15]
    - Part 1 is also contained in ITU-T Rec. H.222
  - Part 9 (Extension for real-time interface) describes extensions to Part 1 for the case where the MPEG-2 packets traverse one or more networks [38]
  - References [16] and [31] contain good introductions to MPEG-2
  - References [32] – [34] contain good descriptions of MPEG-2 timing and jitter

MPEG-2 Transport of Digital Video (Cont.)

- The figure below, taken from [16], compares analog and digital video encoding
  - Part (b) shows that the input to the MPEG coder can be the SDI digital video signal

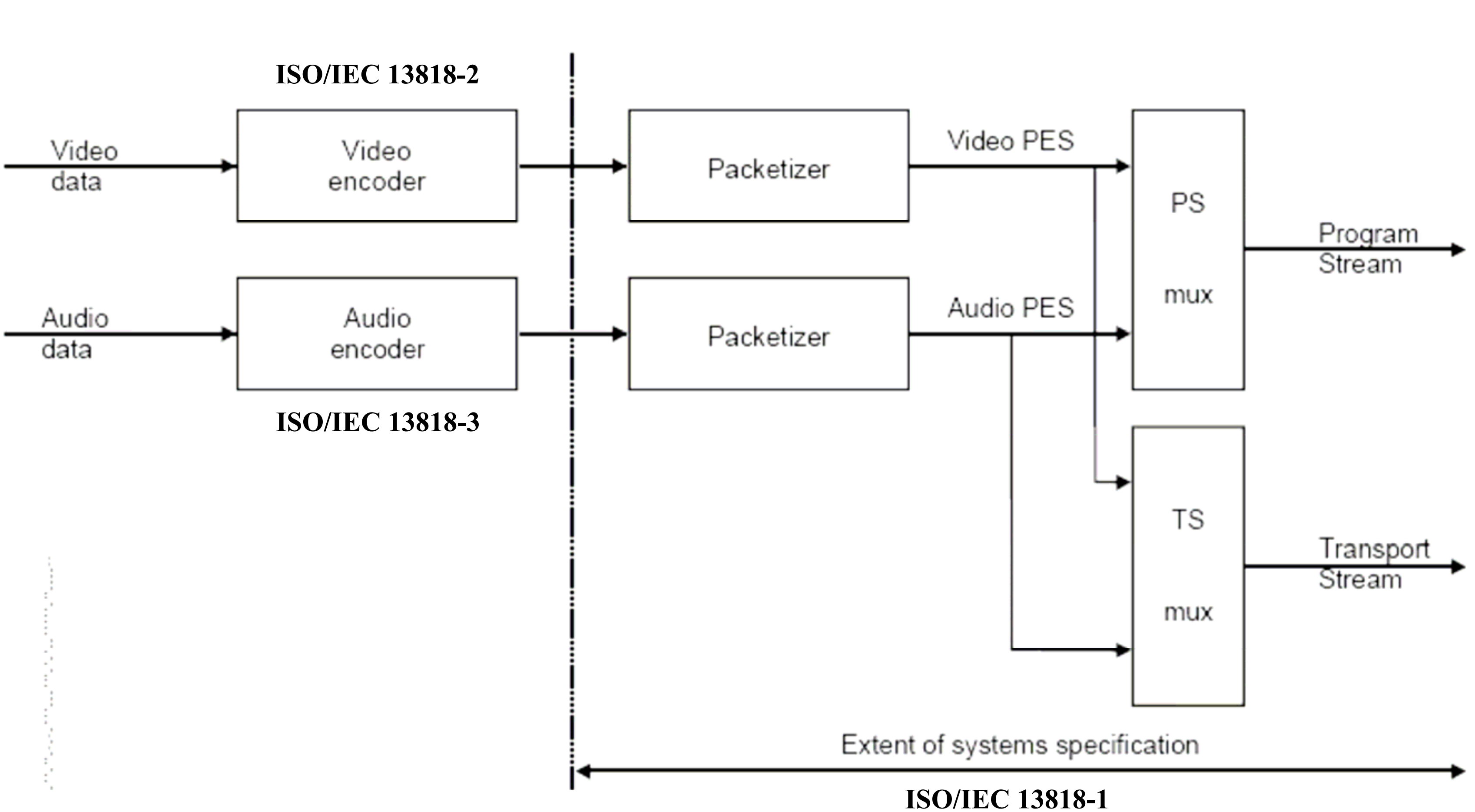


MPEG-2 Transport of Digital Video (Cont.)

- The compressed video and audio are packetized
  - Each such stream (video or audio) obtained from a single source (program) is a Packetized Elementary Stream (PES)
- The video and audio PESs for a program may be multiplexed, along with system information, into a Program Stream (PS)
  - Multiple PES packets are combined into PS Pack
    - Pack contains pack header, followed by system header, followed by PES packets
  - All the information in a PS is traceable to the same clock (because the original digitization of the video and audio of the program were done by the same clock)
- Multiple programs may be multiplexed, along with system information and information about the programs, into a Transport Stream (TS)
  - Each PES packet is mapped into one or more TS packets
    - TS packet size = 188 bytes
    - Last TS packet that contains information from a PES packet is padded to 188 bytes; a new PES packet begins a new TS packet
    - Each TS packet has a header
  - Each program in a TS may be traceable to a different clock; the multiplexing process includes a rate adjustment to the TS Reference Clock (see slides 18 and 19)
- TS packets tend to be much shorter than PS packs

MPEG-2 Transport of Digital Video (Cont.)

- Schematic of MPEG-2 encoding, packetization, multiplexing, and transport (taken from [15], with minor additions)



MPEG-2 Transport of Digital Video (Cont.)

- Compression algorithm may result in the need to decode the PES packets at the receiver out of order
  - This occurs because some compression is achieved by predictive coding
    - A picture may depend on a previous picture, and also on a future picture
      - This scheme takes advantage of the fact that a scene may not change rapidly on the timescale of one frame
    - Note that if the frames are transmitted in the order in which they are encoded, they are transmitted out of order
  - As a result, decoding time may be different from presentation time
  - Each PES packet carries 2 time stamps (TS)
    - Decoding time stamp (DTS) – indicates when the packet should be decoded so that the information is available when needed for presentation at the video receiver
    - Presentation time stamp (PTS) – indicates when the information should be presented at the receiver
    - If the decoding and presentation times are the same, only one TS is sent
  - The DTS and PTS are obtained from values of a local, 90 kHz clock at the encoder
    - Traceable to the 27 MHz System Clock (described below) and referenced to this clock
    - May be obtained by dividing that clock by 300
    - The 90 kHz clock causes a counter to continuously increment, at this rate
    - Value of the counter at the desired time is encoded in a 33-bit TS

MPEG-2 Transport of Digital Video (Cont.)

- Compression algorithm may result in the need to decode the PES packets at the receiver out of order (Cont.)
  - Value of DTS/PTS at receiver indicates time, in units of the 90 kHz counter, that the packet data is to be decoded/presented
    - Therefore, need a clock at the receiver that is synchronized with the System Clock at the encoder
- The System Clock is traceable to the video source clock
  - There is a separate System Clock for each program in a transport stream

MPEG-2 Transport of Digital Video (Cont.)

- The DTS/PTS values are referenced to the System Clock
  - Nominal frequency is 27 MHz
- For Transport Streams, the System Clock is traceable to the video source clock
  - There is a separate System Clock for each program in a transport stream
  - SCFR = ratio of nominal system clock frequency to nominal frame rate
  - Values of SCFR are exact, and are given in [15] for various specified frame rates; e.g.,
    - SCFR = 900900 for nominal frame rate of 30/1.001 Hz (approx. 29.97 Hz)
    - SCFR = 1080000 for nominal frame rate of 25 Hz
    - Other values given in [15]
  - SCASR = ratio of nominal system clock frequency to nominal audio sample rate
    - Note that since the audio and video are part of the same program, they are traceable to the same clock
    - SCASR defined for various nominal audio sample rates (see following slides on digital audio)
      - E.g., 44.1 kHz, 48 kHz

MPEG-2 Transport of Digital Video (Cont.)

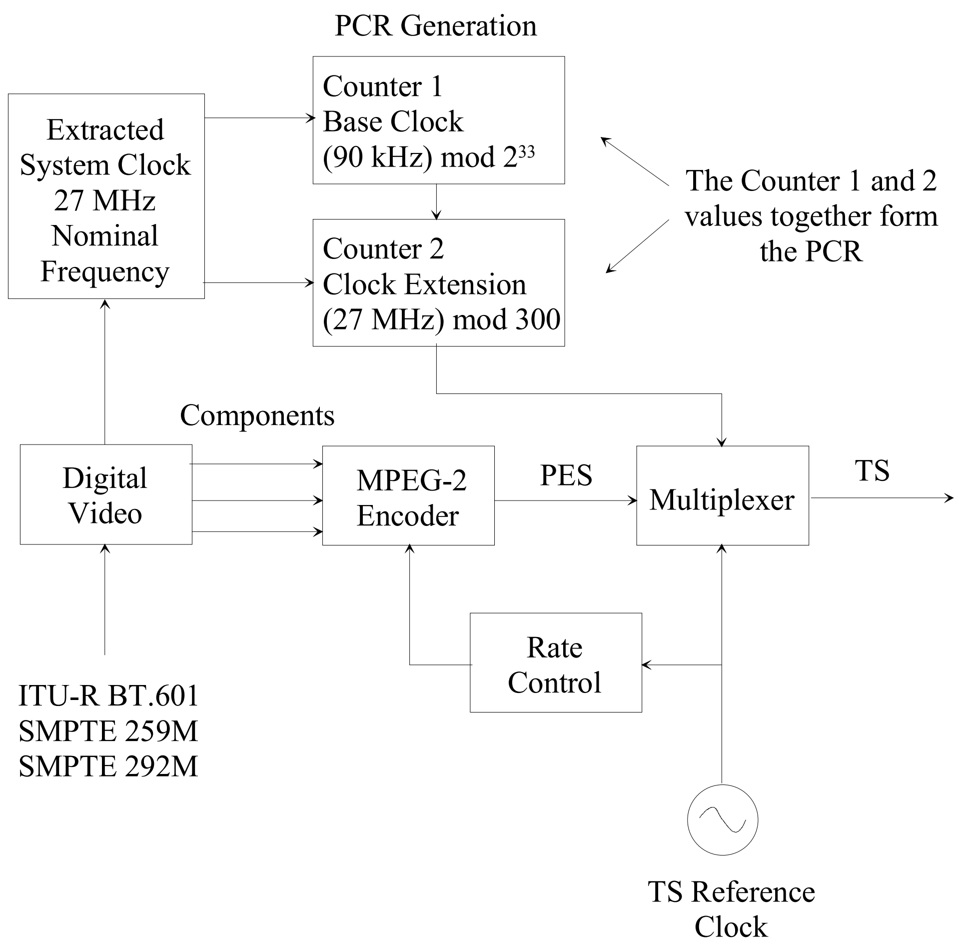
- For Program Streams, the System Clock may be traceable to the video or audio source clock
  - Indicated by flags (system video lock flag and system audio lock flag) in the PS pack header
    - If the system clock is traceable, the same SCFR and SCASR values as for the TS are specified
- For now, we will focus on Transport Streams, and on the case where the System Clock is traceable to the program source clock

MPEG-2 Transport of Digital Video (Cont.)

- The System Clock is transported to the decoder by a 42-bit counter, or time stamp; referred to as
  - Program Clock Reference (PCR) – Transport Stream
  - System Clock Reference (SCR) – Program Stream
  - Elementary Stream Clock Reference (ESCR) – PES
  - In any given transport, only one of these clocks is needed
    - They all work essentially the same way
  - A packet contains a PCR, SCR, or ESCR time stamp
    - The 42-bit counter is driven by the 27 MHz System clock at the encoder
    - TS is carried in a 33-bit base field (that indicates the count divided by 300) and a 9-bit extension (that counts from 0 to 299)
      - This division is used to facilitate obtaining PTS and DTS values
- The System Clock is independent of the TS rate
  - The TS may contain multiple programs with independent system clocks
  - The TS rate is traceable to a separate reference
  - When the TS packets from each program are multiplexed into the TS, the rate of each packet stream must be adjusted to match the TS rate (more precisely, the portion of the TS rate that stream is getting)
  - See figures on next slide (taken from [32])

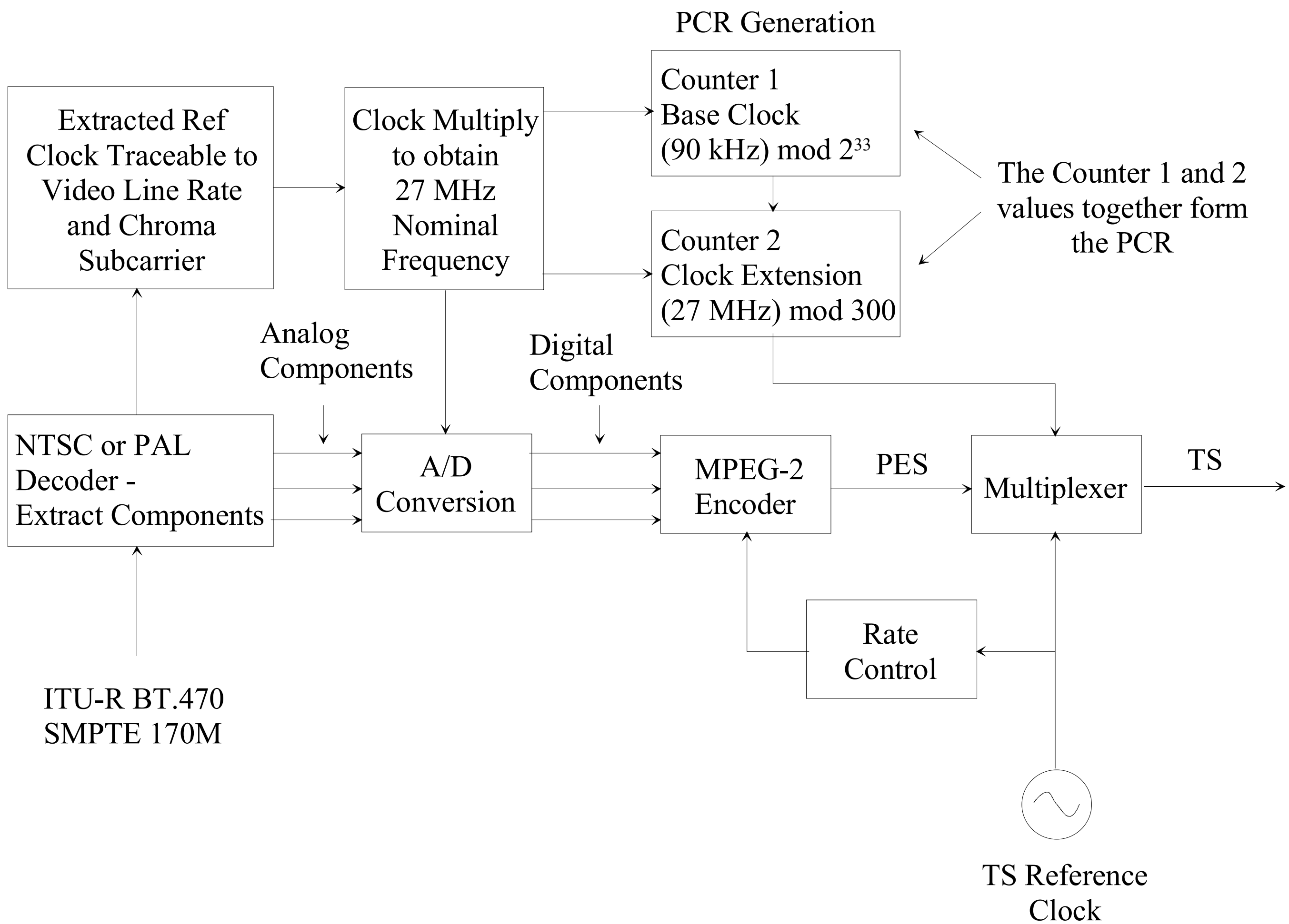
MPEG-2 Transport of Digital Video (Cont.)

- Illustration of generation of PCR values and adjustment of rate of mapping packets into TS to match TS rate (Figure adapted from similar figure in [32]) – digitized component video input



MPEG-2 Transport of Digital Video (Cont.)

- Illustration of generation of PCR values and adjustment of rate of mapping packets into TS to match TS rate (Figure adapted from similar figure in [32]) – analog composite video input



MPEG-2 Transport of Digital Video (Cont.)

- The use of the PCR, SCR, or ESCR time stamp to transport the system clock means there is an underlying assumption that the time to transport the time stamp is fixed
  - Any variation in this time gives rise to jitter and wander
  - This will be discussed shortly
- The PTS and DTS values represent times of events associated with various video frames, namely times the frames should be decoded and/or presented at the egress
  - Since the System Clock is traceable to the source clock for the video, this means that the PTS and DTS are expressed relative to the video source
  - The PTS and DTS values are synchronous with the PCR (or ESCR) values in a TS
    - Also synchronous with the SCR (or ESCR) values in a PS for the case where the system audio and video lock flags indicate that the System Clock is traceable to the program source
  - Based on this description, the granularity of the PTS and DTS values need not give rise to any jitter or wander (analogous to bit-synchronous mapping)

MPEG-2 Transport of Digital Video (Cont.)

- Since the System Clock and associated PCR values are traceable to the source video, they will reflect any jitter and wander present on this source
- However, additional jitter and wander will be added by the MPEG-2 multiplex/demultiplex process and by the transport network (e.g., ResE)
  - The use of PCR time stamps assumes that once a PCR value is obtained at the transmitter, the delay in transporting that value to the receiver is constant
  - Any variation in that delay will show up as added jitter/wander

MPEG-2 Transport of Digital Video (Cont.)

❑Sources of jitter/wander

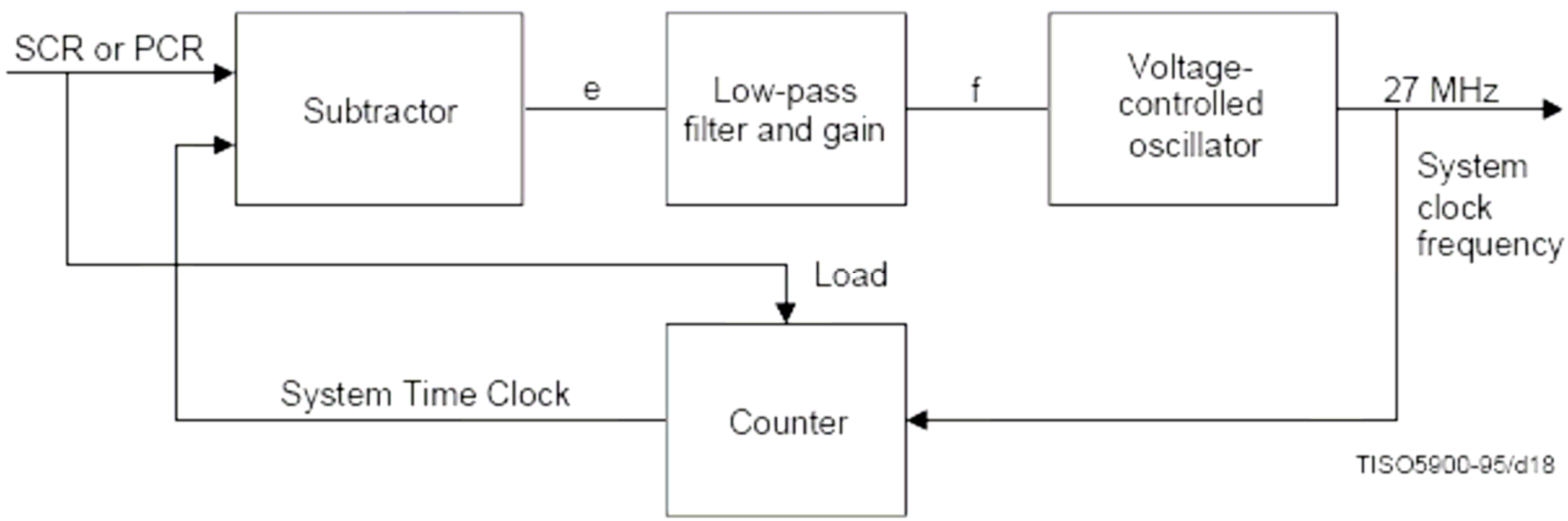
- Jitter/wander present on original digital video signal at source
- Granularity of the 27 MHz clock (approximately 37 ns)
- Delay variation caused by multiplexing or re-multiplexing of programs within a TS (rate matching, delay due to TS packets of different programs arriving simultaneously, etc.)
  - MPEG-2 will adjust PCR values to account for this, but [15] (section 2.4.2.2) allows up to 500 ns of phase error
    - Must be capable of adjusting for up to 4 ms of offset due re-multiplexing (see Section 2.4.2.3 and Annex D of [15])
- Delay variation in transport network
  - Causes PCR/SCR/ESCR time stamps to arrive at times offset from the times reflected by the time stamp values
    - This is the jitter/wander component added by ResE
- Jitter/wander generation in PLLs used to smooth above sources of jitter/wander (see next 2 slides)

MPEG-2 Transport of Digital Video (Cont.)

- One way of recovering the System Clock at the decoder is described in Annex D of [15]
  - Essentially an adaptive clock recovery scheme, i.e., uses a PLL to smooth the arrival stream of packets
  - VCO with nominal center frequency of 27 MHz drives a counter that is compared with incoming PCR/SCR/ESCR
  - Difference signal is amplified and filtered, and result is input to VCO

MPEG-2 Transport of Digital Video (Cont.)

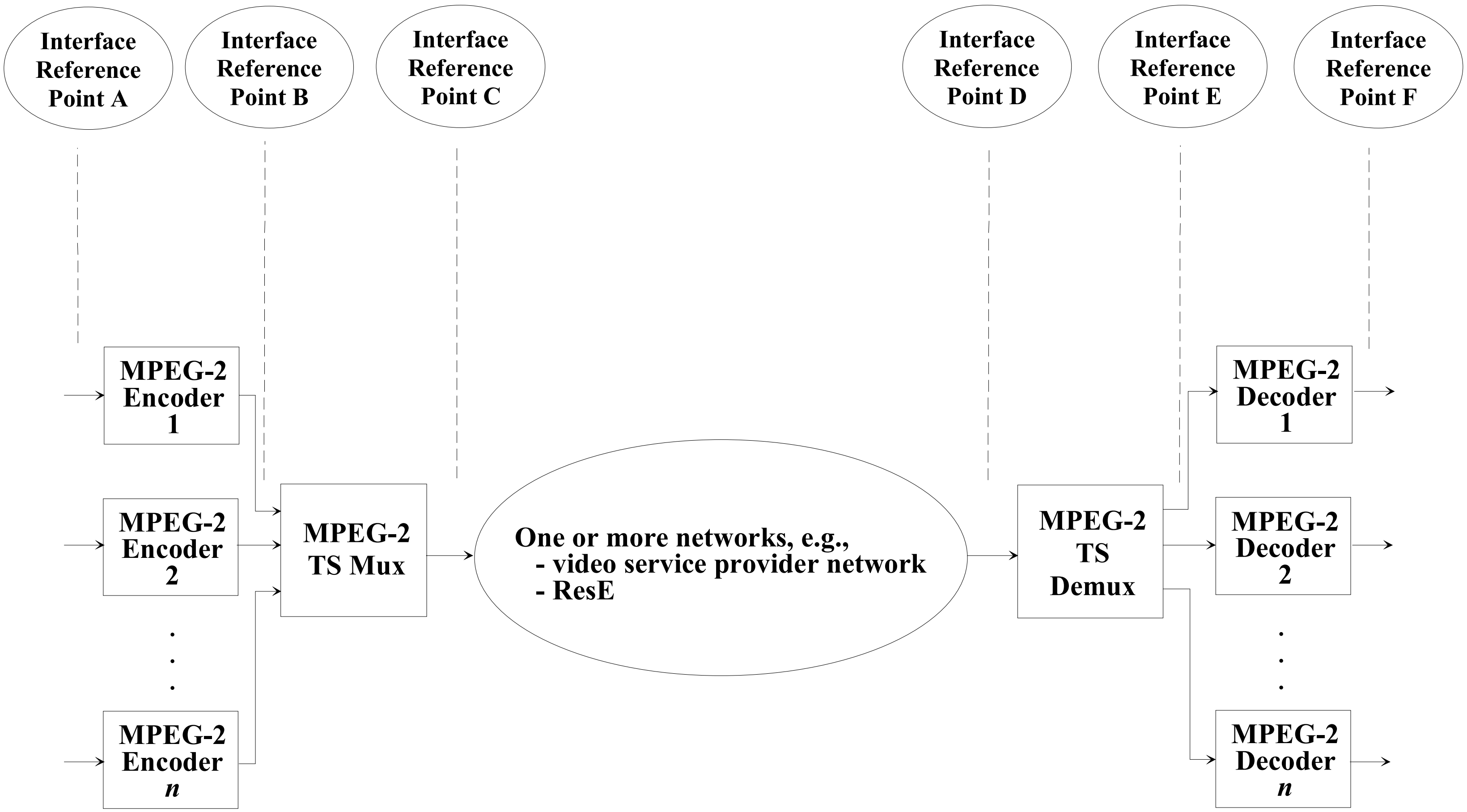
- Schematic of PCR/SCR/ESCR clock recovery PLL (taken from Annex D of [15])
  - Initial value of SCR/PCR/ESCR is loaded into counter to eliminate any initial phase offset



MPEG-2 Transport of Digital Video (Cont.)

- Jitter and wander requirements for MPEG-2
  - Formal requirements are in [15], but see [32] and [34] for good discussions
  - These specify the amount of jitter and wander the MPEG decoder is required to cope with
    - If the requirements were exceeded, the decoded video could contain impairments
- Maximum phase offset in received PCR timestamps
  - $\pm$ 500 ns (section 2.4.2.2 of [15])
    - Includes PCR phase offset due to System clock granularity and multiplexing/re-multiplexing of program
    - **Does not include PCR phase offset due to network-induced jitter**
  - Maximum phase offset for case where the packets traverse one or more networks is specified in [38]
    - $\pm$ 25 μs (section 3.5 of [38])
- Maximum frequency offset implied by PCR timestamps
  - $\pm$ 810 Hz (section 2.4.2.1 of [15])
  - Equivalent to $\pm$ 30 ppm for 27 MHz nominal rate
- Maximum frequency drift rate
  - 75×10^{-3} Hz/s (section 2.4.2.1 of [15])
  - Equivalent to 0.000278 ppm/s for 27 MHz nominal rate

MPEG-2 Transport Across a Network



Reference Points A and F
- E.g., ITU-R BT.601,
SMPTE 259M
SMPTE 292M

Reference Points B and C
- ISO 13818-1;
ISO 13818-2 (Ref. Pt. B);
ISO 13818-3 (Ref. Pt. B)

Reference Points D and E
- ISO 13818-1;
ISO 13883-9;
ISO 13818-2 (Ref. Pt. B)
ISO 13818-3 (Ref. Pt. B)

- Figure adapted from p.10 of [38]

MPEG-2 Transport Across a Network

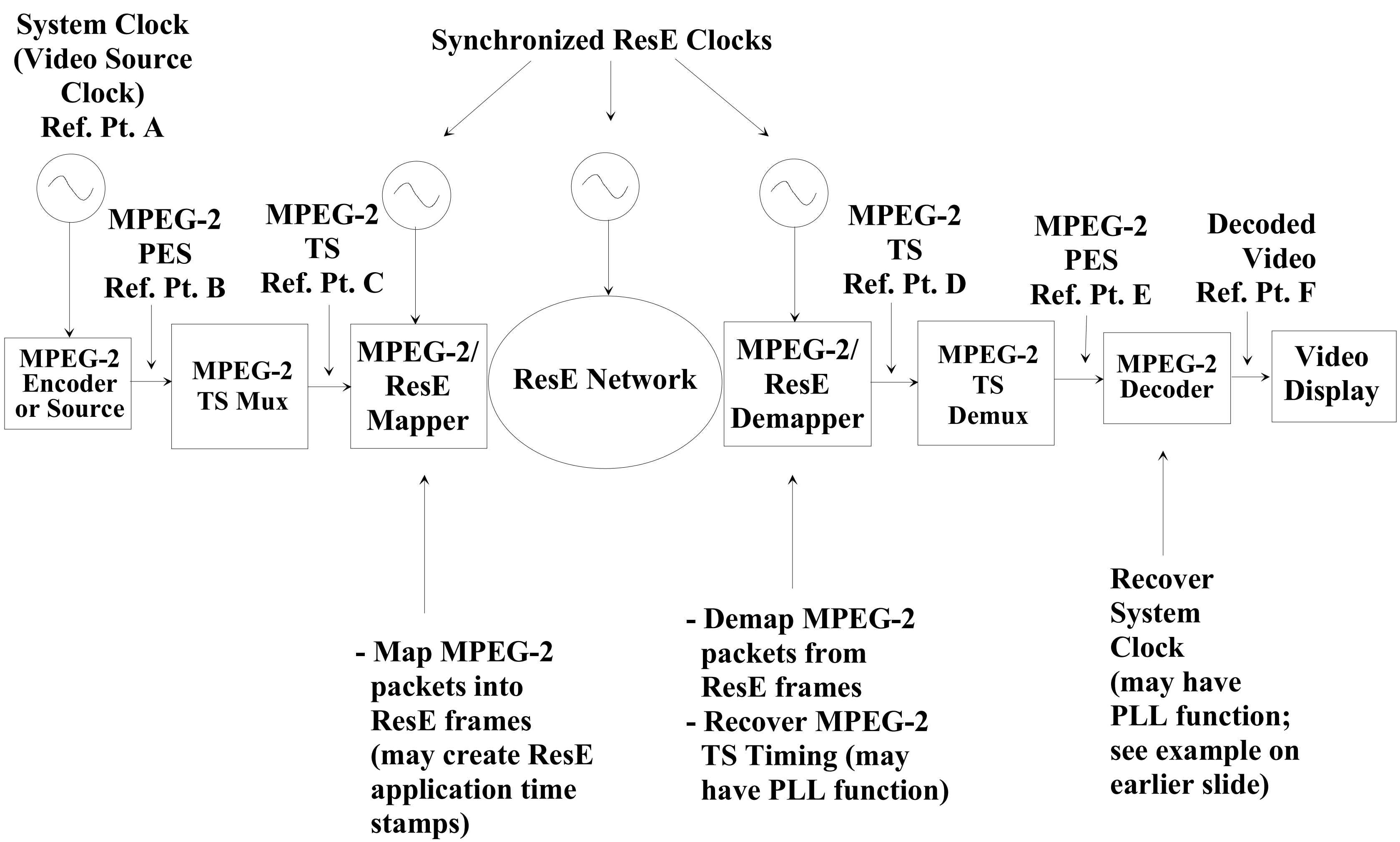
- Reference Points A and F
  - E.g., ITU-R BT.601, SMPTE 259M (SDTV), SMPTE 292M (HDTV)
  - SDTV
    - 0.2 UIpp (high-band and wide-band jitter requirement)
    - NTSC: ±2.79365 ppm (frequency offset), 0.0279365 ppm/s (frequency drift rate)
    - PAL: ±0.225549 ppm (frequency offset), 0.0225549 ppm/s (frequency drift rate)
  - HDTV
    - 1.0 UIpp (wide-band jitter requirement), 0.2 UIpp (high-band jitter requirement)
    - ±10 ppm (frequency offset)
- Reference Points B and C
  - ISO 13818-1; ISO 13818-2, -3 (Reference Point B)
  - Requirements relative to Reference Point A
    - ±500 ns (peak-to-peak phase variation)
    - ±30 ppm (frequency offset)
    - 0.000278 ppm/s (frequency drift rate)
- Reference Points D and E
  - ISO 13818-1; ISO 13818-9; ISO 13818-2, -3 (Reference Point E)
    - Requirements relative to Reference Point A
      - ±25 μs (peak-to-peak phase variation)
      - ±30 ppm (frequency offset)
      - 0.000278 ppm/s (frequency drift rate)

MPEG-2 Transport Across a Network (Cont.)

- Transport of MPEG-2 across a network may involve various scenarios
  - Single ResE network (and no other network transport)
    - E.g., video originates in residence at DVD player, local server, or camcorder
      - Video is transported over ResE and displayed on TV
        - MPEG-2 decoder function may be integrated in TV or exist in a separate unit (e.g., set-top box)
  - Transport across one or more video service provider networks to residence, followed by transport across ResE
    - E.g., video originates in studio of content provider
    - Video either originates in digital form (previously encoded and stored) or A/D conversion occurs in studio
    - Digital video is transported from studio across one or more content provider/service provider networks
      - MPEG-2 encoding may occur at source, or digital video may be initially transported as SDI signal (uncompressed) and MPEG-2 encoding occurs at intermediate point
    - MPEG-2 video is delivered to residence
    - MPEG-2 video is transported across ResE to TV
      - MPEG-2 decoder function may be integrated in TV or exist in a separate unit (e.g., set-top box)

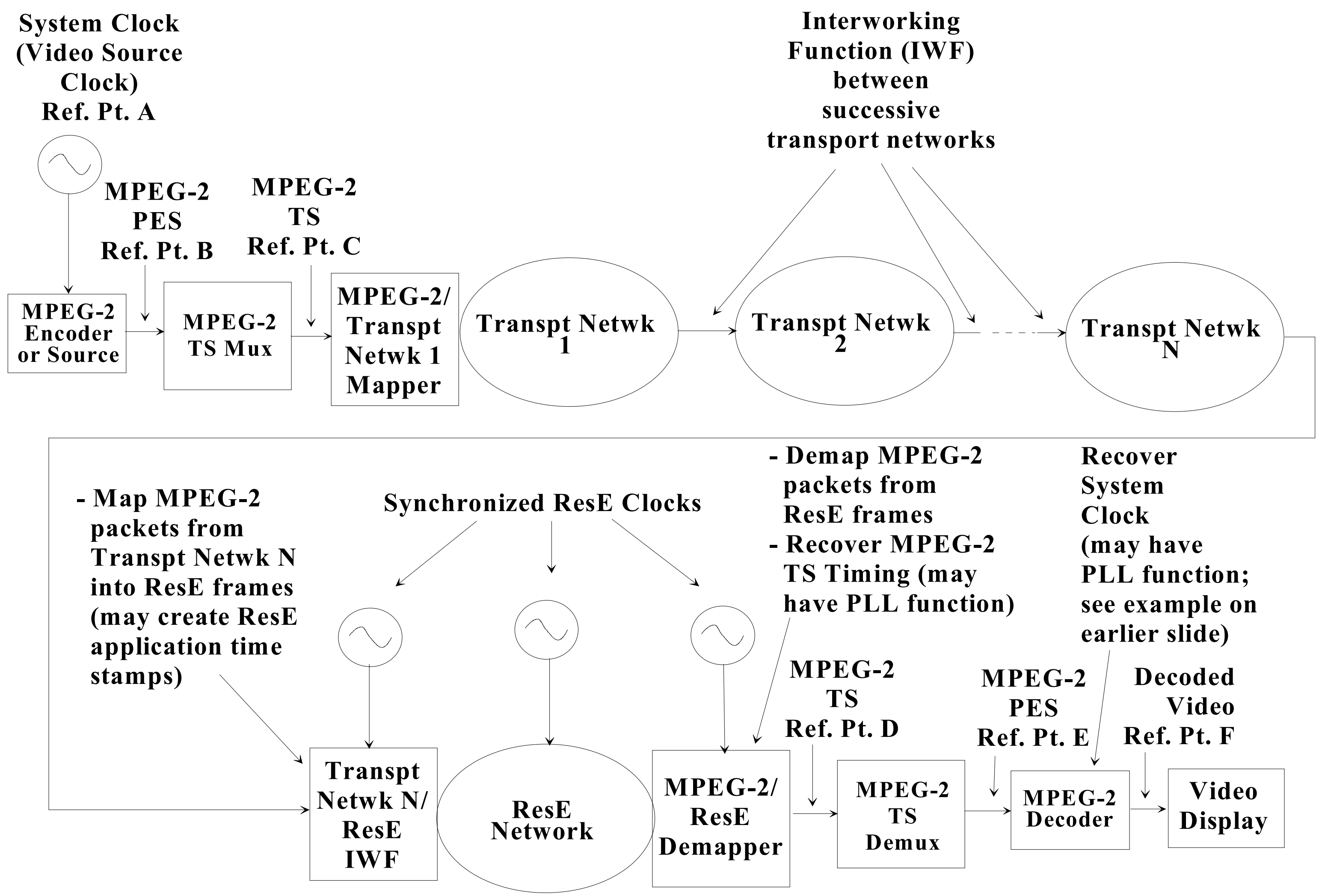
MPEG-2 Transport Across a Network (Cont.)

- Transport across a single ResE network (and no other network)



MPEG-2 Transport Across a Network (Cont.)

- Transport across one or more video service provider networks to residence, followed by transport across ResE



MPEG-2 Transport Across a Network (Cont.)

- Peak-to-peak phase variation, frequency offset, and frequency drift requirement at Reference Point D (MPEG-2/ResE Demapper) is for combined effect of transport across all the networks
  - To reiterate, the requirements are ±25 μs (peak-to-peak phase variation), ±30 ppm (frequency offset), and 0.000278 ppm/s (frequency drift rate)
- If there is only transport across ResE, then the ResE network may generate jitter and wander up to these requirements
- However, if a number of video service provider/content provider networks are present, the ResE network may only use a budgeted allocation
- Problem: we need to know how much of the above peak-to-peak phase variation, frequency offset, and frequency drift requirements can be allocated to ResE
  - i.e, jitter/wander budgets are needed
- ISO 13818-1 and ITU-T H.222 are developed by ISO JTC1/SC29 and by ITU-T SG 16, Q 6
  - Question: Have these groups (or any other group) budgeted jitter and wander to various networks for the case where MPEG-2 is transported across multiple service/content provider networks?
    - If they have not, then how is is ensured that accumulated jitter and wander across a number of transport networks is within limits?

MPEG-2 Transport Across a Network (Cont.)

- Note that from the perspective of ResE, the precise manner in which peak-to-peak phase variation, frequency offset, and frequency drift are budgeted is not important
  - ResE cares mainly about the budget components it gets
  - ResE does not care how the remaining portion is budgeted among the other transport networks
  - ResE also does not care about the details of how the MPEG-2 packets are handed from one transport network to the next

References

1. ITU-R Rec. BT.470-6, *Conventional Television Systems*, ITU-R, Geneva, 1998.
2. SMPTE 170M-1999, *Composite Analog Video Signal – NTSC for Studio Applications*, Society of Motion Picture and Television Engineers, 1999.
3. K. Blair Benson (Deceased, Editor and Coauthor) and Jerry Whitaker (Revised by), *Television Engineering Handbook, Revised Edition*, McGraw-Hill, New York, 1992.
4. Milton Kiver and Milton Kaufman, *Television Electronics, Theory and Service*, Eighth Ed., Van Nostrand Reinhold Company, New York, 1983.
5. Tektronix, *PCR Measurements*, Tektronix, Inc., Document 25W-14617-1, 2003 (available via http://www.tektronix.com/video_audio)

References (Cont.)

6. Tian-Sheuan Chang, *Basics of Video*, VG presentation for Lecture 2 of Multimedia Communication Course, adapted from slides of Prof. Yao Wang and Prof. Hang, National Chiao Tung University, Taiwan (available at http://twins.ee.nctu.edu.tw/courses/multimedia_c_05spring/index.html)
7. SMPTE 259M-1997, 10-Bit 4:2:2 Component and *$4f_{SC}$ Composite Digital Signals – Serial Digital Interface*, Society of Motion Picture and Television Engineers, 1997.
8. ITU-R Rec. BT.601-5, *Studio Encoding Parameters of Digital Television for Standard 4:3 and Wide-Screen 16:9 Aspect Ratios*, ITU-R, Geneva, 1995.
9. SMPTE 292M-1998, *Bit-Serial Digital Interface for High-Definition Television Systems*, Society of Motion Picture and Television Engineers, 1998.
10. SMPTE 318M-1999 (Revision of SMPTE RP 154-1994), *Synchronization of 59.94- or 50-Hz Related Video and Audio Systems in Analog and Digital Areas – Reference Signals*, Society of Motion Picture and Television Engineers, 1999.

References (Cont.)

11. SMPTE 295M-1997, *1920 × 1080 50 Hz – Scanning and Interfaces*, Society of Motion Picture and Television Engineers, 1997.
12. SMPTE 296M-2001, *1280 × 720 Progressive Image Sample Structure – Analog and Digital Representation and Analog Interfaces*, Society of Motion Picture and Television Engineers, 2001.
13. ISO/IEC 13818-2, *Information technology – Generic coding of moving pictures and associated audio information: Video*, ISO/IEC, Geneva, 2000 (same as ITU-T Rec. H.262, ITU-T, Geneva, 2000).
14. ISO/IEC 13818-3, *Information technology – Generic coding of moving pictures and associated audio information: Audio*, ISO/IEC, Geneva, 1996.
15. ISO/IEC 13818-1, *Information technology – Generic coding of moving pictures and associated audio information: Systems*, ISO/IEC, Geneva, 2000 (same as ITU-T Rec. H.222.0, ITU-T, Geneva, 2000).
16. Tektronix, *A Guide to MPEG Fundamentals and Protocol Analysis (including DVB and ATSC)*, Tektronix, Inc., Document 25W-11418-1, 2002 (available via http://www.tektronix.com/video_audio).

References (Cont.)

17. *DIGITabilit: crash course on digital audio interfaces* (parts 1.1 – 1.5), available via http://www.tnt-audio.com/clinica/diginterf1_e.html (links to all 5 parts at the end of part 1)
18. IEC 60958-1, *Digital Audio Interface – Part1: General*, International Electrotechnical Commission, Geneva, 2004.
19. IEC 60958-3, *Digital Audio Interface – Part3: Consumer Applications*, International Electrotechnical Commission, Geneva, 2003.
20. IEC 60958-4, *Digital Audio Interface – Part4: Professional Applications (TA4)*, International Electrotechnical Commission, Geneva, 2003.
21. EBU Tech. 3250-E, *Specification of the Digital Audio Interface*, European Broadcasting Union, Geneva, 2004.
22. AES3-2003, *AES Recommended practice for digital audio engineering -- Serial transmission format for two-channel linearly represented digital audio data* (Revision of AES3-1992, including subsequent amendments), Audio Engineering Society, 2003.
23. AES5-2003: *AES recommended practice for professional digital audio -- Preferred sampling frequencies for applications employing pulse-code modulation* (Revision of AES5-1997), Audio Engineering Society, 2003.

References (Cont.)

24. AES11-2003: *AES recommended practice for digital audio engineering - Synchronization of digital audio equipment in studio operations* (Revision of AES11-1997), Audio Engineering Society, 2003.
25. Julian Dunn, *Jitter Theory*, Audio Precision Technote, TN-23, 2000 (available via http://www.audioprecsion.com)
26. Julian Dunn, *The AES3 and IEC60958 Digital Interface*, Audio Precision Technote, TN-26, 2001 (available via http://www.audioprecsion.com)
27. Julian Dunn, *Measurement Techniques for Digital Audio*, Audio Precision Application Note #5, 2004 (available via http://www.audioprecsion.com)
28. Julian Dunn, Barry A. McKibben, Roger Talyor, Chris Travis, *Towards Common Specifications for Digital Audio Interface Jitter*, 95th AES Convention, Preprint 3705, New York, October, 1993.
29. Julian Dunn, *Considerations for Interfacing Digital Audio Equipment to the Standards AES-3, AES-5, and AES-11*, AES 10th International Conference, Preprint 3712, London, September, 1991
30. Eric Benjamin and Benjamin Gannon, *Theoretical and Audible Effects of Jitter on Digital Audio Quality*, 105th AES Convention, Preprint Preprint 4826, San Francisco, August, 1998.

References (Cont.)

31. Michael Orzessek and Peter Somer, *ATM and MPEG-2, Integrating Digital Video into Broadband Networks*, Prentice Hall PTR, Upper Saddle River, NJ, 1998.
32. Tektronix, *PCR Measurements*, Tektronix, Inc., Document 25W-14617-1, 2003 (available via http://www.tektronix.com/video_audio).
33. Tektronix, *A Layman's Guide to PCR Measurements*, Tektronix, Inc., Technical Brief, Document 25W-14706-0, 2001 (available via http://www.tektronix.com/video_audio).
34. ETSI TR 101 290, *Digital Video Broadcasting (DVB): Measurement guidelines for DVB systems*, V.1.2.1 (2001-05).
35. ITU-T Recommendation G.810, *Definitions and Terminology for Synchronization Networks*, ITU-T, Geneva, August, 1996, Corrigendum 1, November, 2001.
36. Stefano Bregni, *Synchronization of Digital Telecommunications Networks*, Wiley, New York, 2002.
37. Geoffrey M. Garner, *Timing in Global Optical Networks*, Optical Networks Magazine, January/February, 2003, pp. 36 – 52.

References (Cont.)

38. ISO/IEC 13818-9, *Information technology – Generic coding of moving pictures and associated audio information: Extension for real-time interface for systems decoders*, ISO/IEC, Geneva, 1996.
39. T1A1.1/2000-012R2, *Draft American National Standard for Transport of MPEG2 Encoded Video over ATM*, 2000, (available via http://www.atis.org).
40. Dan Wolaver, *Calculation of DS3 Video Codec Phase Transfer*, Tektronix Contribution to Committee T1X1.3, T1X1.3/96-063, July, 1996 (available via http://www.atis.org).
41. Dan Wolaver, *Comparison of MTIE, Frequency Response, and Derivatives as Bounds on Phase*, Tektronix Contribution to Committee T1X1.3, T1X1.3/96-064, July, 1996 (available via http://www.atis.org).
42. Ralf Steinmetz, *Human Perception of Jitter and Media Synchronization*, IEEE JSAC, Vol. 14, No. 1, January, 1996, pp. 61 – 72.
43. Alexei Beliaev, *Latency Sensitive Application Examples*, Gibson Labs, part of *Residential Ethernet Tutorial*, IEEE 802.3 meeting, March, 2005.