End-to-end Delay of Videoconferencing over Packet Switched Networks

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September 2003

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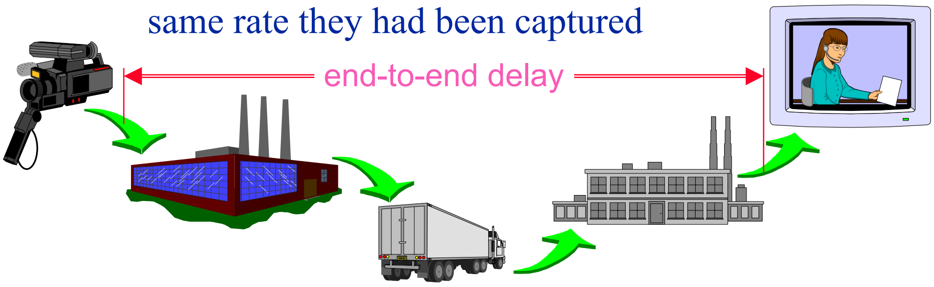
Videoconferencing Requirements

- Bound on end-to-end delay
  - 100 ms
- Synchronization
  - the receiver continuously shows pictures at the same rate they had been captured



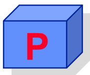
Goals

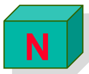
Identify components of the end-to-end delay

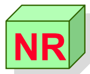
Find out which configurations of the videoconferencing system allow the end-to-end delay to be kept below the 100 ms bound

Components of End-to-end Delay

- *Processing* delay
  - e.g., encoding
- *Network* delay
  - e.g., shaping, propagation, queueing
- Resynchronization
  - *processing resynchronization* delay
    - e.g., from constant bit rate to constant frame rate
  - *network resynchronization* delay
    - e.g., jitter compensation





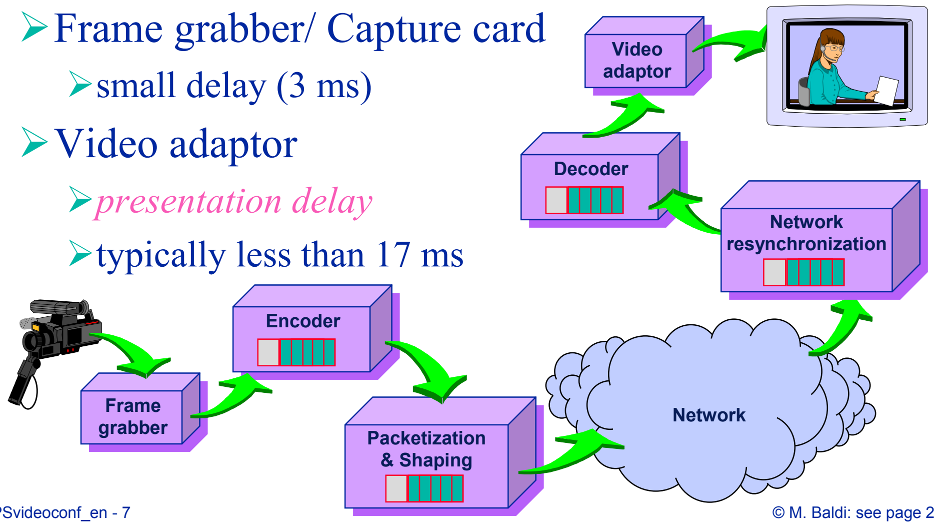


Configurations

	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ **1**	$\frac{F_r}{B} + Sw + P + P_d$ **2**	$\frac{F_r}{C} + P + Q_M + E_r + P_d$ **4** $S_n + \frac{P_s}{C} + P + Q_M + E_r + P_d$	$L \cdot T_f + P_d$ **3**
CBR MPEG	$S_c + P + D + P_d$	$S_c + Sw + P + D + P_d$ **5**	$S_c + P + \frac{P_s}{C} +$ **6** $+ Q_M + E_r + D + P_d$	$S_c + L \cdot T_f + D + P_d$
VBR MPEG	$C_M + P + D + P_d$		$C_M + S_n + P + \frac{P_s}{C} +$ **7** $+ Q_M + E_r + D + P_d$	$C_M + L \cdot T_f + D + P_d$ **8**

System model

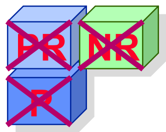
- Frame grabber/ Capture card
  - small delay (3 ms)
- Video adaptor
  - *presentation delay*
  - typically less than 17 ms



Road Map

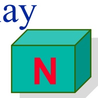
	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	1	$\frac{F_r}{B} + Sw + P + P_d$ 2	$\frac{F_r}{C} + P + Q_M + E_r + P_d$ 4 $S_n + \frac{P_s}{C} + P + Q_M + E_r + P_d$	$L \cdot T_f + P_d$ 3
CBR MPEG	$S_c + P + D + P_d$	$S_c + Sw + P + D + P_d$ 5	$S_c + P + \frac{P_s}{C} +$ 6 $+ Q_M + E_r + D + P_d$	$S_c + L \cdot T_f + D + P_d$
VBR MPEG	$C_M + P + D + P_d$		$C_M + S_n + P + \frac{P_s}{C} +$ 7 $+ Q_M + E_r + D + P_d$	$C_M + L \cdot T_f + D + P_d$ 8

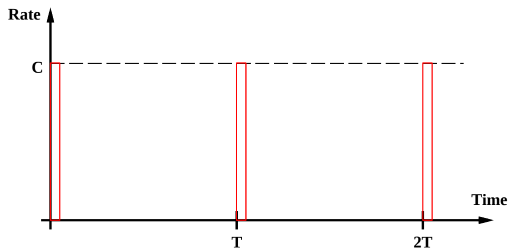
Dedicated link



$$\Delta_{raw}^{ded} = \frac{F_r}{C} + P + P_d$$

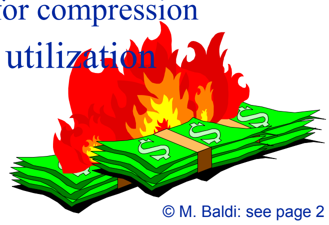
- P propagation delay
- C link capacity
- F_r picture dimension
- P_d presentation delay
  - synchronize adaptor and capture card





Dedicated link

- For example C = 100 Mb/s
  - QCIF: F_r = 176x144 = 198 kb → $\frac{F_r}{C} = 1.98$ ms
  - HDTV: F_r = 1920x1080 = 16200 kb → $\frac{F_r}{C} = 162$ ms
- For real-time video ⇒ $\frac{F_r}{C} \leq T$
  - HDTV (30 fps) C > 486 Mb/s → need for compression
- ☹ Short delay ⇒ large capacity ⇒ low utilization
  - QCIF example: 3%



Road Map

	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ N	2	$\frac{F_r}{C}+P+Q_M+E_r+P_d$ 4 $S_n+\frac{P_s}{C}+P+Q_M+E_r+P_d$	$L \cdot T_f + P_d$ 3
CBR MPEG	$S_c + P + D + P_d$	$S_c + Sw + P + D + P_d$ 5	$S_c + P + \frac{P_s}{C} +$ 6 $+ Q_M + E_r + D + P_d$	$S_c + L \cdot T_f + D + P_d$
VBR MPEG	$C_M + P + D + P_d$		$C_M + S_n + P + \frac{P_s}{C} +$ 7 $+ Q_M + E_r + D + P_d$	$C_M + L \cdot T_f + D + P_d$ 8

Circuit Switching

~~PR~~ ~~NR~~ ~~P~~

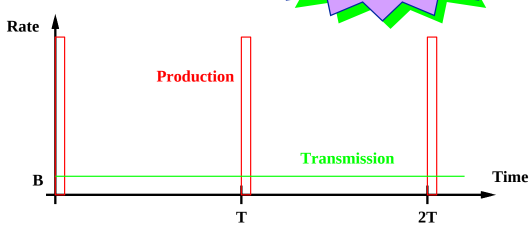
$$\Delta_{raw}^{CS} = \frac{F_r}{B} + Sw + P + P_d$$

- P propagation delay
- Sw switching delay
- B circuit bandwidth
- F_r picture dimension

N

See it

$$\frac{F_r}{B} = T$$

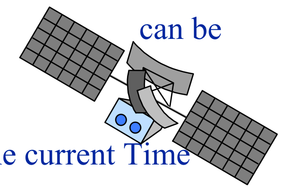


Road Map

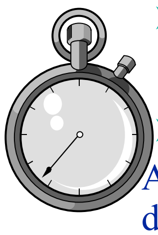
	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ N	$\frac{F_r}{B} + Sw + P + P_d$ N	$\frac{F_r}{C} + P + Q_M + E_r + P_d$ 4 $S_n + \frac{P_s}{C} + P + Q_M + E_r + P_d$	3
CBR MPEG	$S_c + P + D + P_d$	$S_c + Sw + P + D + P_d$ 5	$S_c + P + \frac{P_s}{C} +$ 6 $+ Q_M + E_r + D + P_d$	$S_c + L \cdot T_f + D + P_d$
VBR MPEG	$C_M + P + D + P_d$		$C_M + S_n + P + \frac{P_s}{C} +$ 7 $+ Q_M + E_r + D + P_d$	$C_M + L \cdot T_f + D + P_d$ 8

Time Driven Priority

- Nodes share a global timing reference
  - external reference (e.g., GPS) can be used



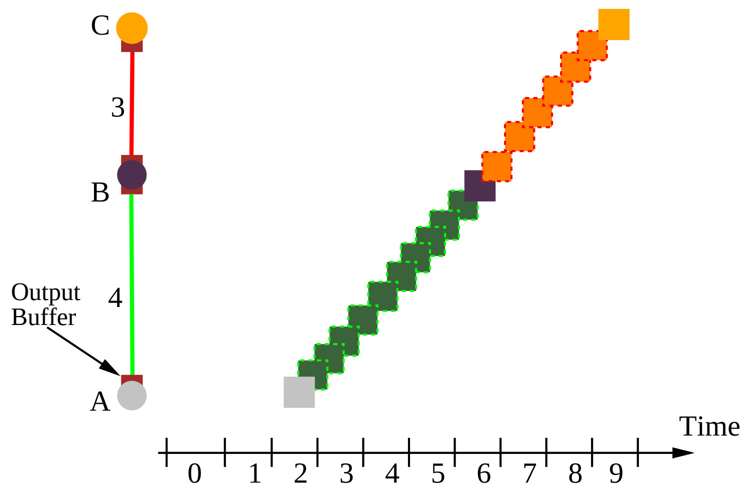
- Time is divided in *Time Frames*
  - each node has the same notion of the current Time Frame
    - beginning and end
  - typical duration $T_f = 125\ \mu s$



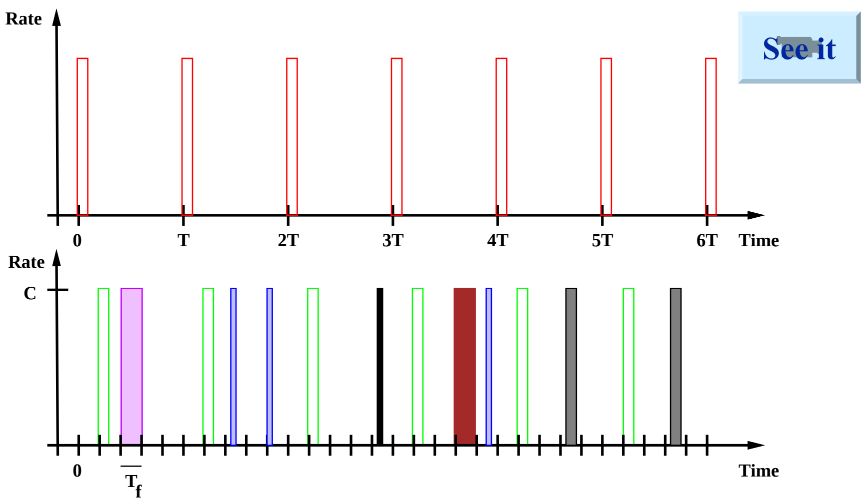
See it

A fixed amount of bits $T_f \cdot C$ can be sent on a link during a Time Frame

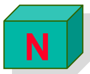
RISC-like forwarding of packets



Traffic Multiplexing

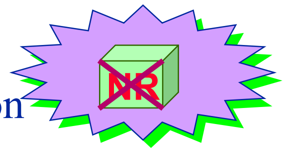


End-to-end Delay

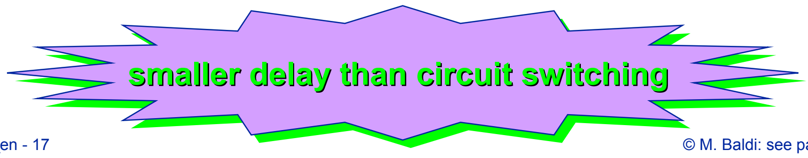


$$\Delta_{raw}^{TDP} = L \cdot T_f + P_d$$

- ➔ L depends on number of hops
- ➔ Network jitter $2 \cdot T_f$
  - ➔ no need for resynchronization



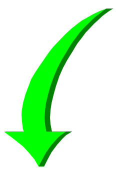
- ➔ P_d presentation delay

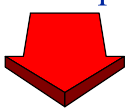


Comparison with Dedicated Link

System parameters

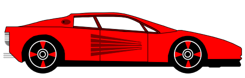
- Capacity $C = 100$ Mb/s
- $L = 3$, $P = 0$, $Sw = 0$
- QCIF at 15 fps

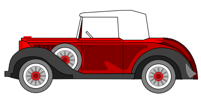




$$\Delta_{raw}^{ded} = 1.98 \text{ ms} \qquad \Delta_{raw}^{TDP} = 2.175 \text{ ms} \qquad \Delta_{raw}^{CS} = 66.67 \text{ ms}$$

97 % of dedicated link capacity unused





Road Map

	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ N	$\frac{F_r}{B} + Sw + P + P_d$ N	4	$L \cdot T_f + P_d$ N
CBR MPEG	$S_c + P + D + P_d$	$S_c + Sw + P + D + P_d$ 5	$S_c + P + \frac{P_s}{C} + Q_M + E_r + D + P_d$ 6	$S_c + L \cdot T_f + D + P_d$
VBR MPEG	$C_M + P + D + P_d$		$C_M + S_n + P + \frac{P_s}{C} + Q_M + E_r + D + P_d$ 7	$C_M + L \cdot T_f + D + P_d$ 8

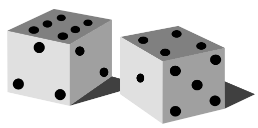
Network Delay

N

- Fixed transmission and propagation delay
- Variable queueing delay
  - queueing policies
  - network load

NR

Non deterministic behavior

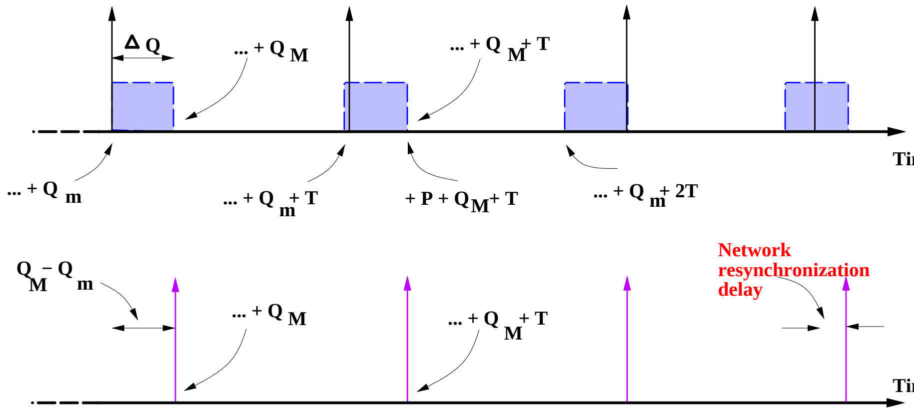


Network delay is not bound deterministically

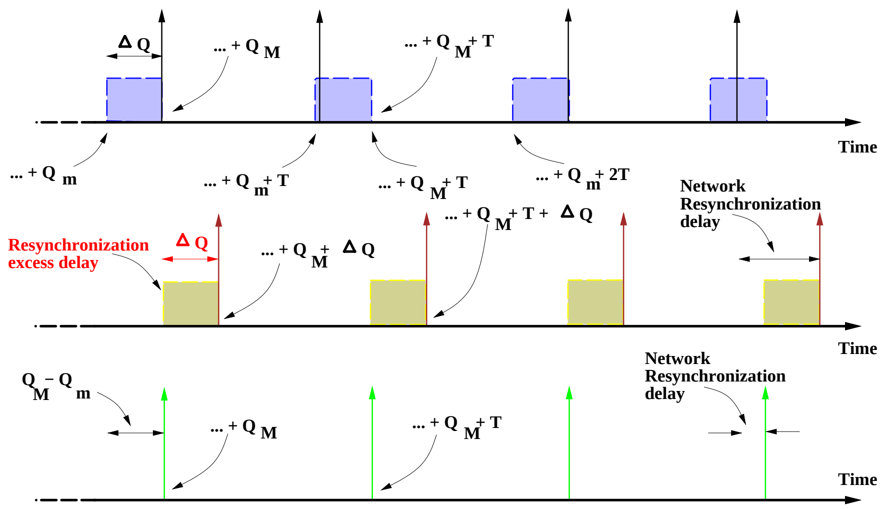
Network Resynchronization

NR

Use a guessed bound Q_M on network delay



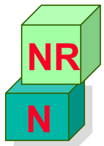
Resynchronization Excess Delay



End-to-end Delay

$$\Delta_{raw}^{bursty} = \frac{F_r}{C} + P + Q_M + E_r + P_d$$

- $E_r \in [0, \Delta Q]$ resynchronization excess delay
  - constant during the videoconference call
- $\Delta Q = Q_M - Q_m$ maximum jitter
- Q_M (**guess on**) maximum queueing delay
- Q_m minimum queuing delay
- P propagation delay
- C capacity of links



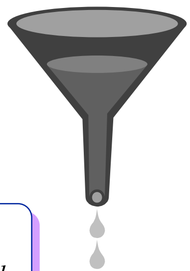
→ F_r raw picture dimension

→ P_d presentation delay

See it

Traffic Shaping

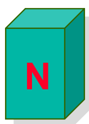
- For example, *leaky bucket*
  - token generation rate B
  - token bucket size A



$$\Delta_{raw}^{TS} = S_n + \frac{P_s}{C} + P + Q_M + E_r + P_d$$

- *network shaping delay*
- P_s packet size

$$S_n = \frac{F_r - A}{B}$$

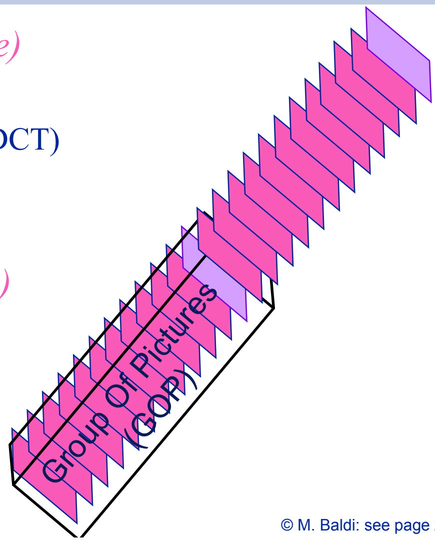


Road Map

	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ N	$\frac{F_r}{B} + Sw + P + P_d$ N	$\frac{F_r}{C} +$ NR $E_r + P_d$ $S_n + \frac{P_s}{C}$ N $E_r + P_d$	$L \cdot T_f + P_d$ N
CBR MPEG	$S_c + P + D + P_d$	$S_c + Sw + P + D + P_d$ 5	$S_c + P + \frac{P_s}{C} +$ 6 $+ Q_M + E_r + D + P_d$	$S_c + L \cdot T_f + D + P_d$
VBR MPEG	$C_M + P + D + P_d$		$C_M + S_n + P + \frac{P_s}{C} +$ 7 $+ Q_M + E_r + D + P_d$	$C_M + L \cdot T_f + D + P_d$ 8

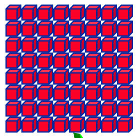
MPEG Compression Standard

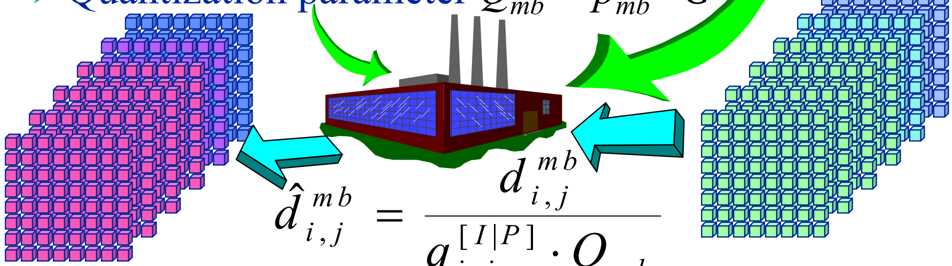
- *Intra-frame coding (I-Frame)*
  - 8x8 blocks
  - Discrete Cosine Transform (DCT)
  - Quantization
  - Encoding
- *Predictive coding (P-Frame)*
  - MacroBlock (MB)
  - motion estimation
  - motion compensation



Quantization

- Quantization matrices $q_{i,j}^{[I|P]}$
- Global distortion level G
- MB activity level p_{mb}
- Quantization parameter $Q_{mb} = p_{mb} \cdot G$

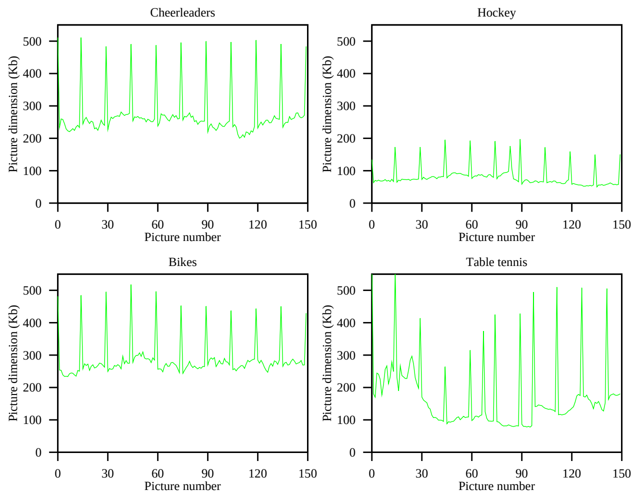




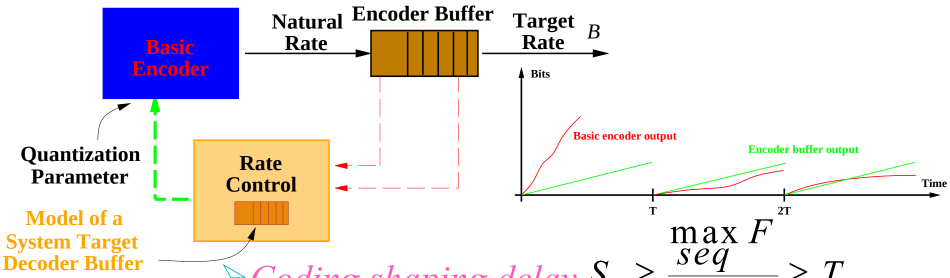
$$\hat{d}_{i,j}^{mb} = \frac{d_{i,j}^{mb}}{q_{i,j}^{[I|P]} \cdot Q_{mb}}$$

Cheerleaders Scene

Natural MPEG Bit Rate



CBR MPEG Encoder

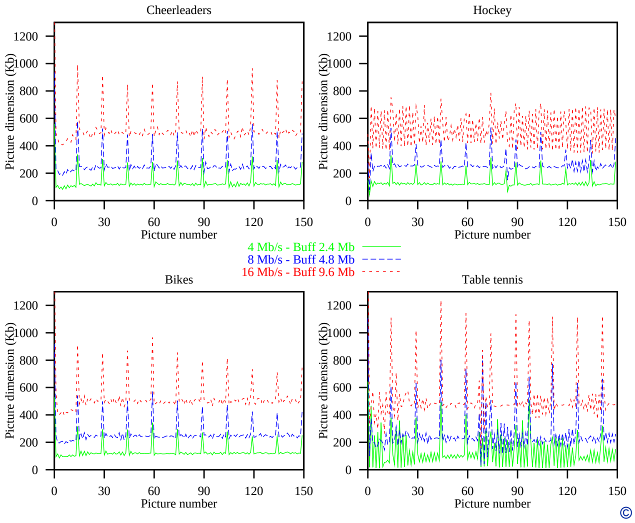


- *Coding shaping delay* $S_c \geq \dfrac{\max_{seq} F}{B} \geq T$

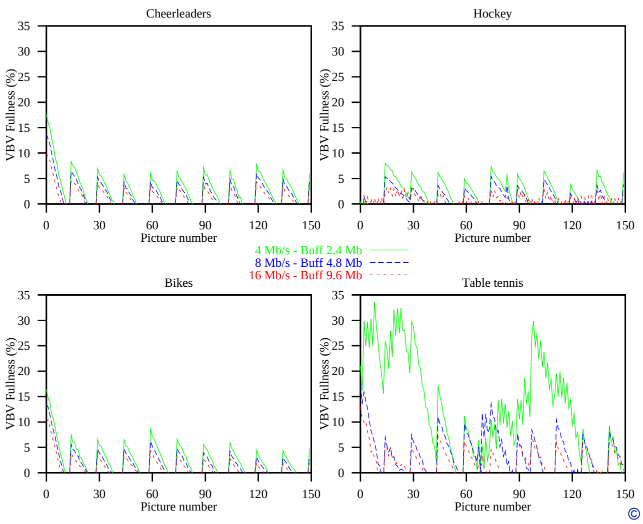
  - variable delay introduced by encoder buffer
  - processing resynchronization delay introduced by the decoder

The delay is larger than the video frame period

Dimension of Pictures



Video Buffer Verifier Fullness



Video Buffer Verifier and Picture Quality

- V_s Video Buffer Verifier (VBV) size determines
  - variability of picture dimension

$$\max_{seq} F \leq V_s \qquad\qquad \min_{seq} F \geq 2 \cdot B \cdot T - V_s$$

  - visual quality of encoded video

High and uniform quality ⇒ large VBV
Up to ***GOP size*** for static scenes

Video Buffer Verifier and Delay

$$S_c \geq \frac{\max_{seq} F}{B}$$

- $\max_{seq} F$ is not known when starting encoding
- dimension the system using an upper bound (V_s)

$$S_c \geq \frac{V_s}{B}$$

High picture quality ⇒ large delay
Up to *GOP period* for static scenes

Road Map

	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ N	$\frac{F_r}{B} + Sw + P + P_d$ N	$\frac{F_r}{C} + \ldots E_r + P_d$ NR $S_n + \frac{P_s}{C} \ldots E_r + P_d$ N	$L \cdot T_f + P_d$ N
CBR MPEG	$S_c + P + D + P_d$	5	$S_c + P + \frac{P_s}{C} +$ 6 $+ Q_M + E_r + D + P_d$	$S_c + L \cdot T_f + D + P_d$
VBR MPEG	$C_M + P + D + P_d$		$C_M + S_n + P + \frac{P_s}{C} +$ 7 $+ Q_M + E_r + D + P_d$	$C_M + L \cdot T_f + D + P_d$ 8

Circuit Switching

~~NR~~

$$\Delta_{CBR}^{CS} = S_c + Sw + P + D + P_d$$

- S_c coding shaping delay
- D *decoding delay*
- Sw switching delay
- P propagation delay
- P_d presentation delay

PR
P
N

Road Map

	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ N	$\frac{F_r}{B} + Sw + P + P_d$ N	$\frac{F_r}{C} +$ NR $E_r + P_d$ $S_n + \frac{P_s}{C}$ N $E_r + P_d$	$L \cdot T_f + P_d$ N
CBR MPEG	$S_c + P + D + P_d$	S PR $P + D + P_d$ P N	6	$S_c + L \cdot T_f + D + P_d$
VBR MPEG	$C_M + P + D + P_d$		$C_M + S_n + P + \frac{P_s}{C} +$ 7 $+ Q_M + E_r + D + P_d$	$C_M + L \cdot T_f + D + P_d$ 8

Packet Switching with Statistical Multiplexing

$$\Delta_{CBR}^{SM} = S_c + \frac{P_s}{C} + P + Q_M + E_r + D + P_d$$

- $E_r \in [0, \Delta Q]$ resynchronization excess delay
- $\Delta Q = Q_M - Q_m$ maximum jitter
- Q_M (**guess on**) maximum queueing delay
- Q_m minimum queueing delay
- P propagation delay
- P_s packet size
- C link capacity

NR
N

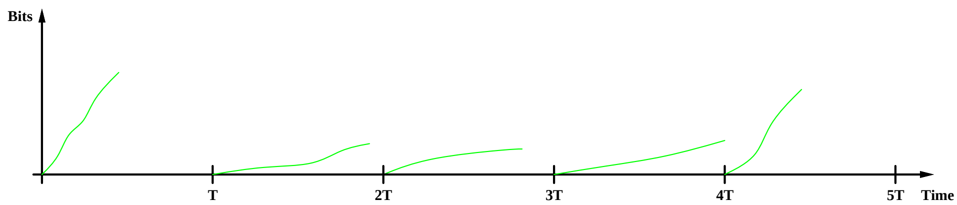
- S_c coding shaping delay
- D decoding delay
- P_d presentation delay

PR
P

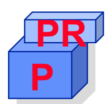
Road Map

	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ N	$\frac{F_r}{B} + Sw + P + P_d$ N	$\frac{F_r}{C} +$ NR $E_r + P_d$ $S_n + \frac{P_s}{C}$ N $E_r + P_d$	$L \cdot T_f + P_d$ N
CBR MPEG	$S_c + P + D + P_d$	S_c PR $+ D + P_d$ P N	PR NR $+$ P N P_d	$S_c + L \cdot T_f + D + P_d$
VBR MPEG	$C_M + P + D + P_d$		7	$C_M + L \cdot T_f + D + P_d$ 8

VBR MPEG Encoding



- C_M *maximum coding delay*
  - the decoder buffer compensates variations of coding delay
    - processing resynchronization delay



$C_M \leq T$

Packet Switching with Statistical Multiplexing

$$\Delta_{VBR}^{TS} = C_M + S_n + \frac{P_s}{C} + P + Q_M + E_r + D + P_d$$

- C_M maximum coding delay
- S_n network shaping delay
- Q_M (**guess on**) maximum queueing delay
- $E_r \in [0, \Delta Q]$ resynchronization excess delay
- P_s packet size

PR
P

NR
N

Problems with VBR MPEG and Statistical Multiplexing

MPEG stream not compatible with traffic shaper parameters

Discard data

Use best effort service

Not acceptable

compressed video is sensitive to losses

Forward adaptation

Hierarchical encoding

Feedback & adaptation

Road Map

	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ N	$\frac{F_r}{B} + Sw + P + P_d$ N	$\frac{F_r}{C} +$ NR $E_r + P_d$ $S_n + \frac{P_s}{C}$ N $E_r + P_d$	$L \cdot T_f + P_d$ N
CBR MPEG	$S_c + P + D + P_d$	S_c PR P N $+ D + P_d$	PR NR $+$ P N P_d	$S_c + L \cdot T_f + D + P_d$
VBR MPEG	$C_M + P + D + P_d$		$C + S$ PR NR $+$ $+$ P N P_d	8

Packet Switching with Time Driven Priority

~~NR~~

$$\Delta_{VBR}^{TDP} = C_M + L \cdot T_f + D + P_d$$

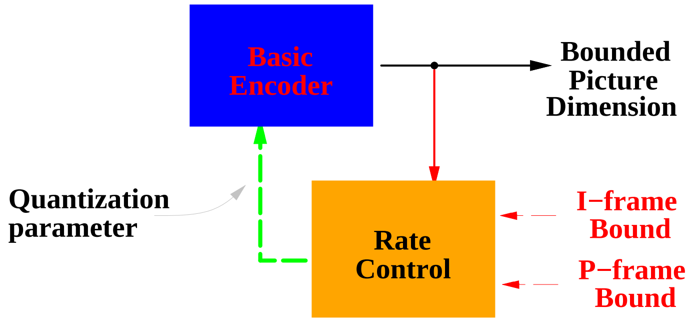
PR
P

- C_M maximum coding delay
- L depends on number of hops
- P_d presentation delay

N

Picture dimension must be bound

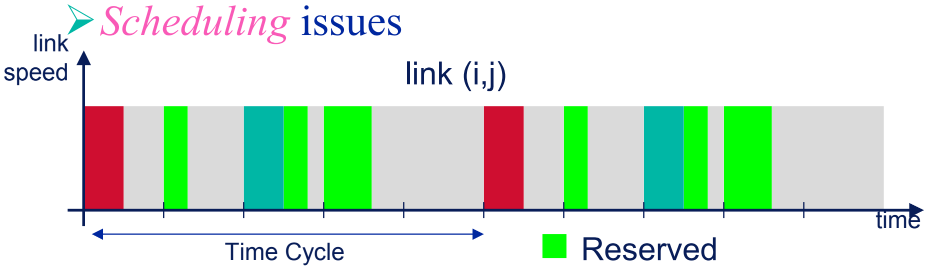
Bounding Picture Dimension



Different bounds for I-frames and P-frames

Resource Allocation

- *Time cycle* equal to video frame period ***T***
- Reserve 1 time frame per time cycle
- *Scheduling* issues



- Videoconference call 1
- Videoconference call 2
- Reserved (guaranteed traffic)
- Non reserved (usable for best effort)

Network Shaping Delay

$$S_n + L \cdot T_f + P_d \pm T_f$$

$$S_n = S_t \in [0, T]$$

- S_n *network shaping delay*
- $S_t = 0$ if the capture card is synchronized with network interface

$$C \geq \frac{F_r}{T}$$

  - QCIF C > 1.5 Gb/s
  - HDTV C > 130 Gb/s

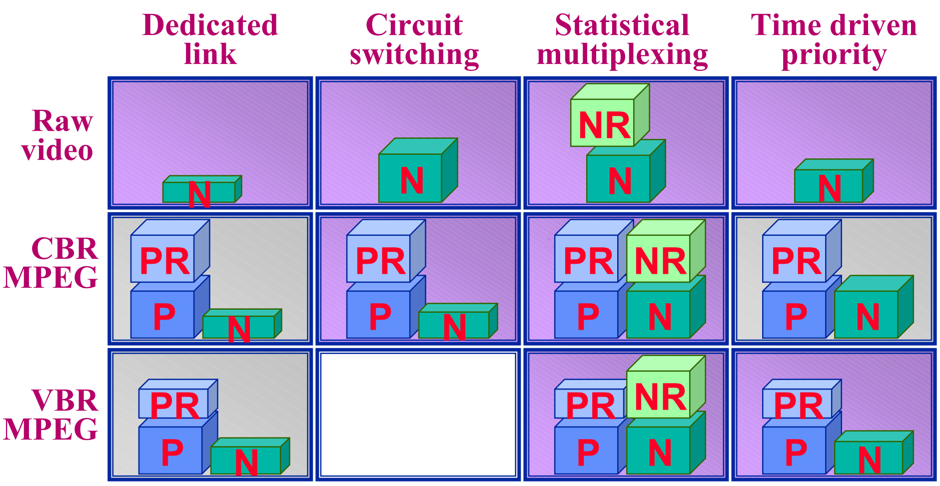
Network Shaping Delay

$$S_n = S_t + (N_r - 1)$$

$$N_r \geq \left| \frac{F_r}{T_f \cdot C} \right|$$

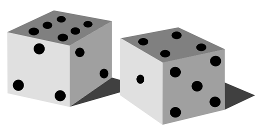
- N_r depends on scheduling
  - constant
  - fixed at reservation time

The Complete Picture



Conclusions

Statistical Multiplexing
- non deterministically bound delay
- large guessed bound



CBR MPEG Encoding
- long coding shaping delay

up to GOP period

Conclusions

Time driven priority

- ➔ strict bound on jitter (250 μs)
- ➔ VBR MPEG encoder

The *end-to-end* delay can be *less* than a video frame period *T*