



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

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September 2003



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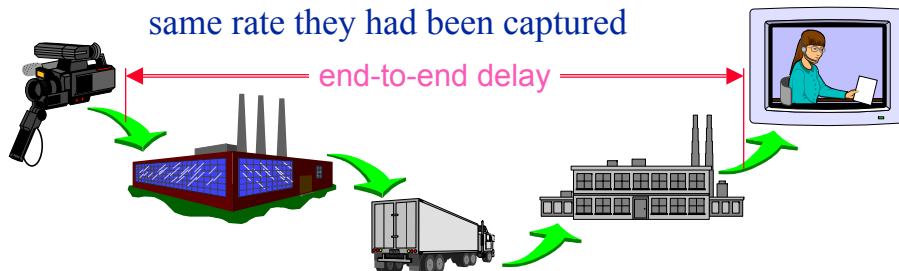
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Videoconferencing Requirements

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



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Goals

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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

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Components of End-to-end Delay

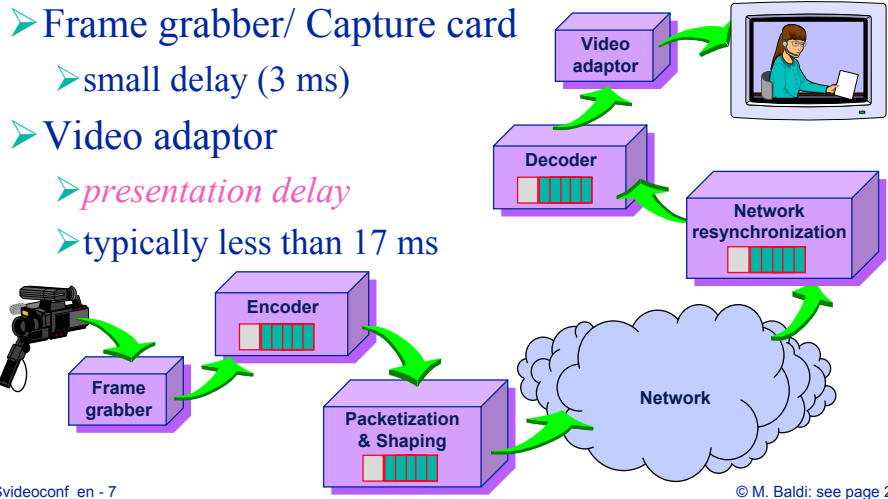
- **Processing** delay P
 - e.g., encoding
- **Network** delay N
 - e.g., shaping, propagation, queuing
- **Resynchronization**
 - **processing resynchronization** delay PR
 - e.g., from constant bit rate to constant frame rate
 - **network resynchronization** delay NR
 - e.g., jitter compensation



Configurations

	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ 1	$\frac{F_r}{B} + S_w + P + P_d$ 2	$\frac{F_r}{C} + P + Q_M + E_r + P_d$ 4	$L \cdot T_f + P_d$ 3
CBR MPEG	$S_c + P + D + P_d$	$E_c + S_w + P + D + P_d$ 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

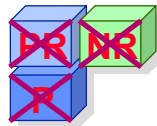
System model



Road Map

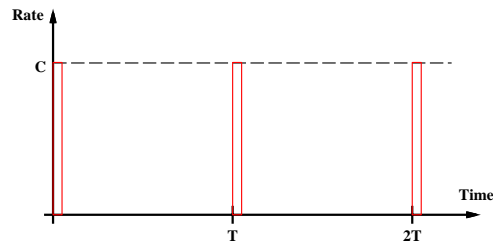
	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	1	$\frac{F_r}{B} + S_w + P + P_d$ 2	$\frac{F_r}{C} + P + Q_M + E_r + P_d$ 4	$L \cdot T_f + P_d$ 3
CBR MPEG	$S_c + P + D + P_d$	$S_c + S_w + P + D + P_d$ 5	$S_c + P + \frac{P_s}{C} + Q_M + E_r + D + P_d$ 6	$S_c +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

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

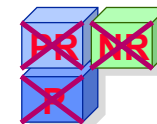
- For example $C = 100$ Mb/s
 - QCIF: $F_r = 176 \times 144 = 198$ kb → $\frac{F_r}{C} = 1.98$ ms
 - HDTV: $F_r = 1920 \times 1080 = 16200$ kb → $\frac{F_r}{C} = 162$ ms
- For real-time video ⇒ $\frac{F_r}{C} \leq T$
 - HDTV (30 fps) $C > 486$ Mb/s → need for compression
 - ☹ Short delay ⇒ large capacity ⇒ low utilization
 - QCIF example: 3%



Road Map

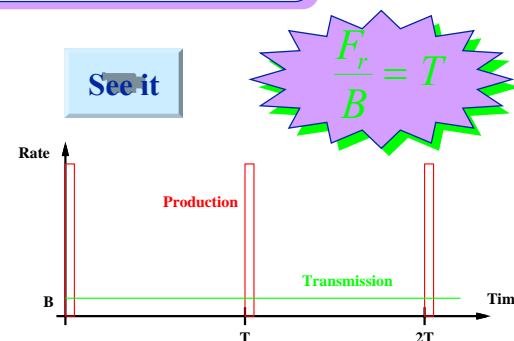
	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ 	2	$\frac{F_r}{C} + P + Q_M + E_r + P_d$ 4 $S_n + \frac{P_s}{C} + P + Q_M + E_r + P_d$	$L \cdot T_f + P_d$ 3
CBR MPEG	$S_c + P + D + P_d$	$S_c + S_w + P + D + P_d$ 5	$S_c + P + \frac{P_s}{C}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

Circuit Switching





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

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



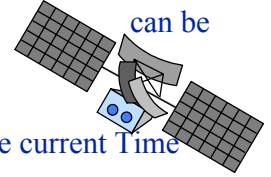
Road Map

	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ 	$\frac{F_r}{B} + S_w + P + P_d$ 	$\frac{F_r}{C} + P + Q_M + E_r + P_d$ $S_r + \frac{P_s}{C} + P + Q_M + E_r + P_d$ 4	3
CBR MPEG	$S_c + P + D + P_d$	$S_c + S_w + P + D + P_d$ 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

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



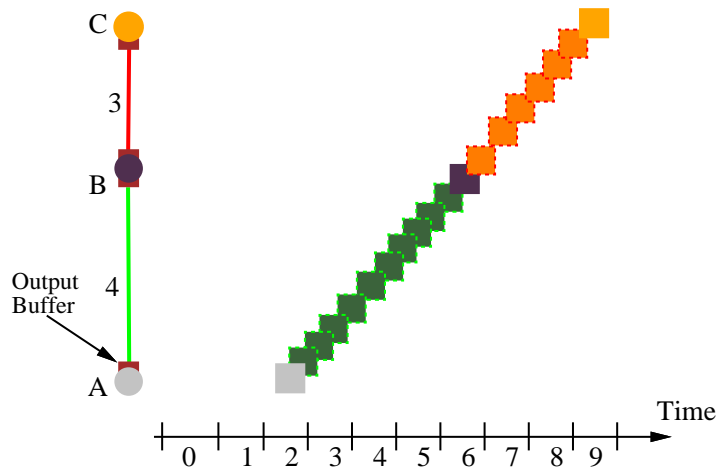
➤ beginning and end

➤ typical duration $T_f = 125 \mu s$

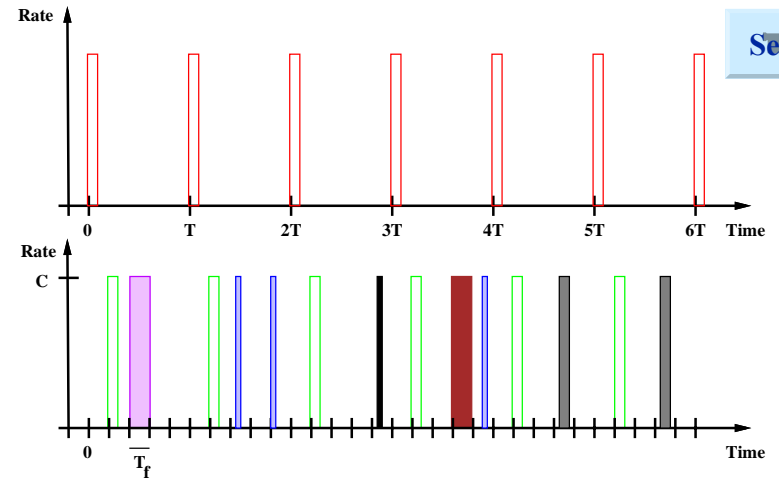
A fixed amount of bits $T_f \cdot C$ can be sent on a link during a Time Frame

See it

RISC-like forwarding of packets



Traffic Multiplexing



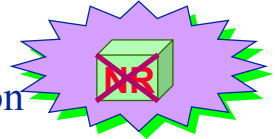
See it

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

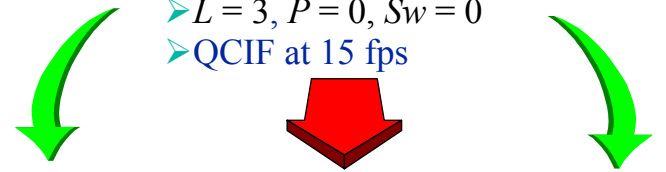


smaller delay than circuit switching

Comparison with Dedicated Link

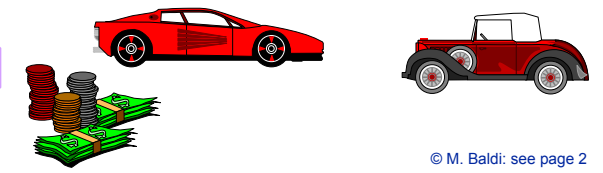
System parameters

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



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

97 % of dedicated link capacity unused



Road Map

	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ 	$\frac{F_r}{B} + S_w + P + P_d$ 	4	$L \cdot T_f + P_d$
CBR MPEG	$S_c + P + D + P_d$	$S_c + S_w + P + D + P_d$ 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

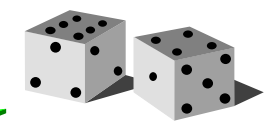
Network Delay



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



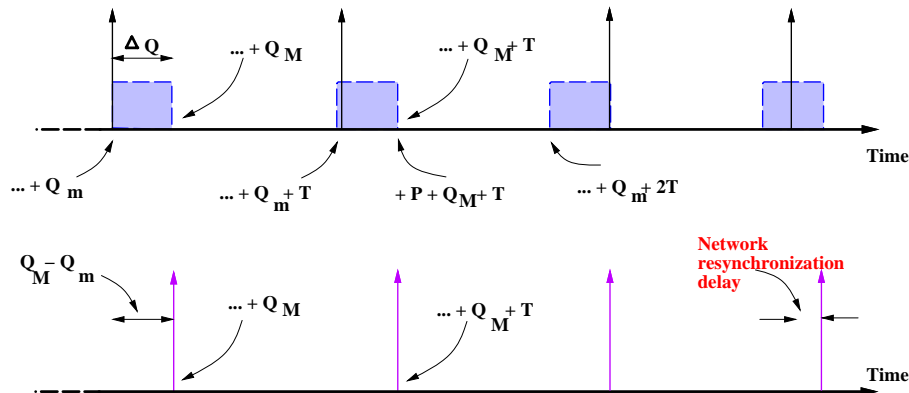
Non deterministic behavior



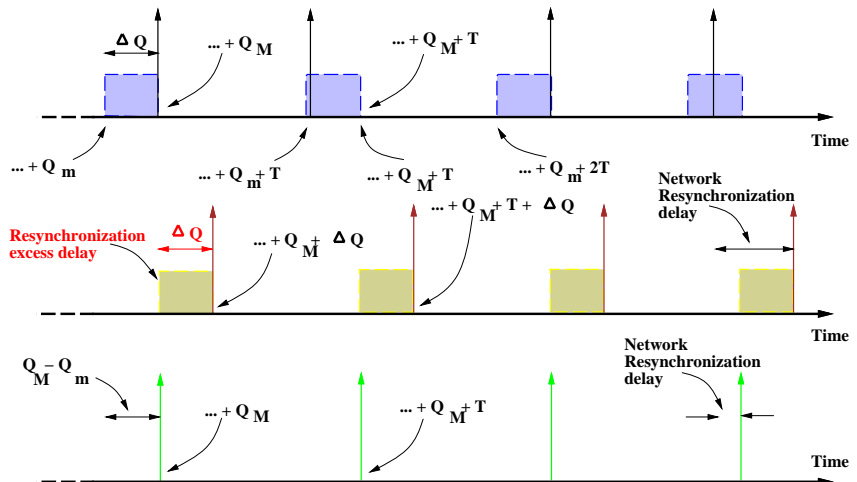
Network delay is not bound deterministically

Network Resynchronization

Use a **guessed bound** Q_M on network delay



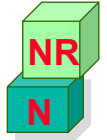
Resynchronization Excess Delay



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 queuing delay
- Q_m minimum queuing delay
- P propagation delay
- C capacity of links



- ➔ F_r raw picture dimension
- ➔ P_d presentation delay



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* $S_n = \frac{F_r - A}{B}$
- P_s packet size



Road Map

	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ 	$\frac{F_r}{B} + S_w + P + P_d$ 	$\frac{F_r}{C} + E_r + P_d$  $S_n + \frac{P_s}{C} + E_r + P_d$ 	$L \cdot T_f + P_d$ 
CBR MPEG	$S_c + P + D + P_d$	$S_c + S_w + P + D + P_d$ 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

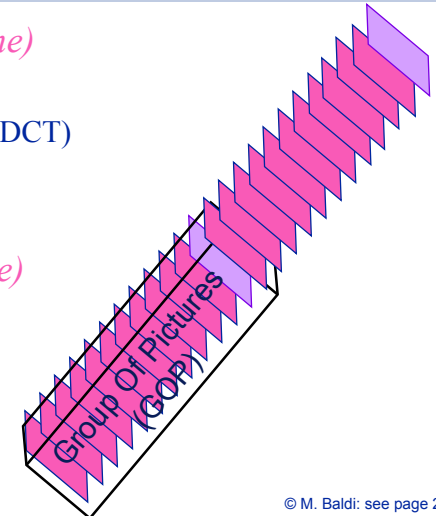
MPEG Compression Standard

Intra-frame coding (I-Frame)

- 8x8 blocks
- Discrete Cosine Transform (DCT)
- Quantization
- Encoding

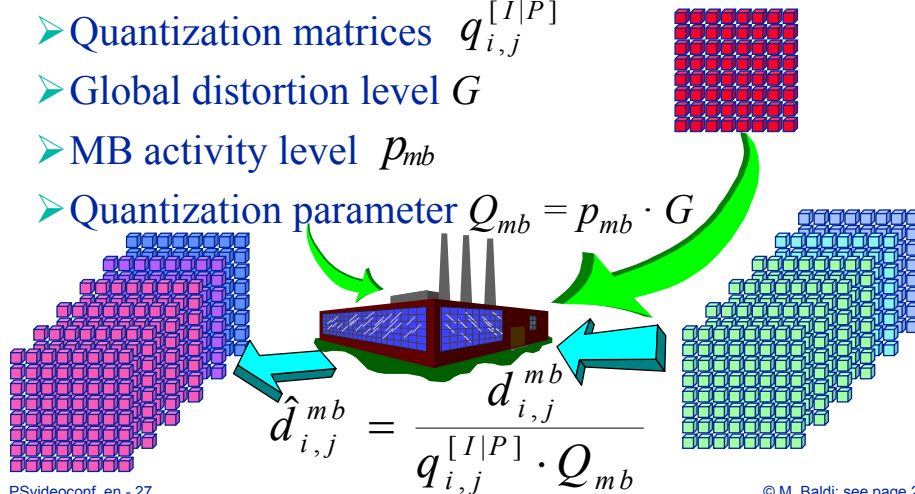
Predictive coding (P-Frame)

- 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 $Q_{mb} = p_{mb} \cdot G$

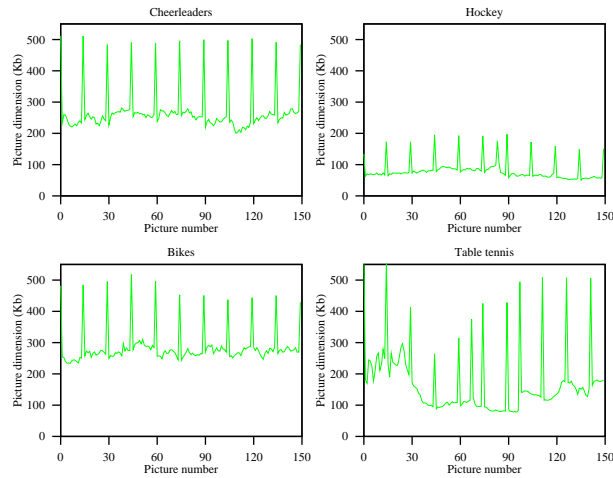


Cheerleaders Scene

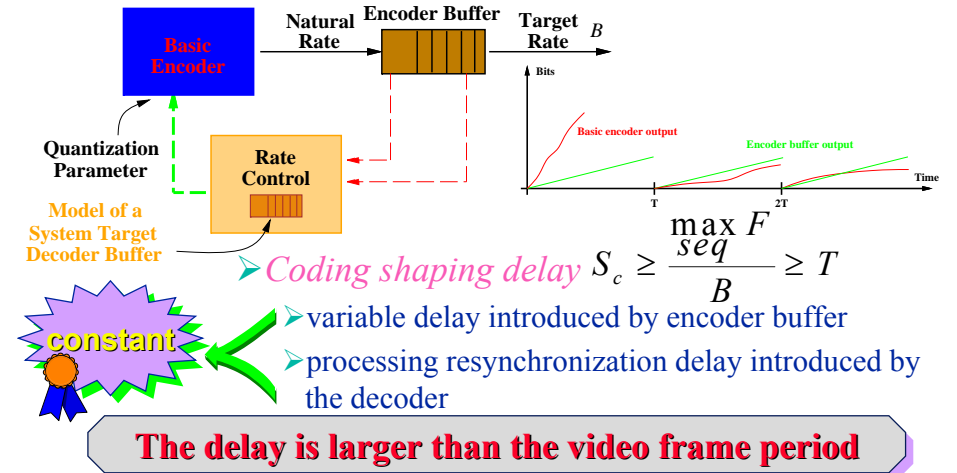




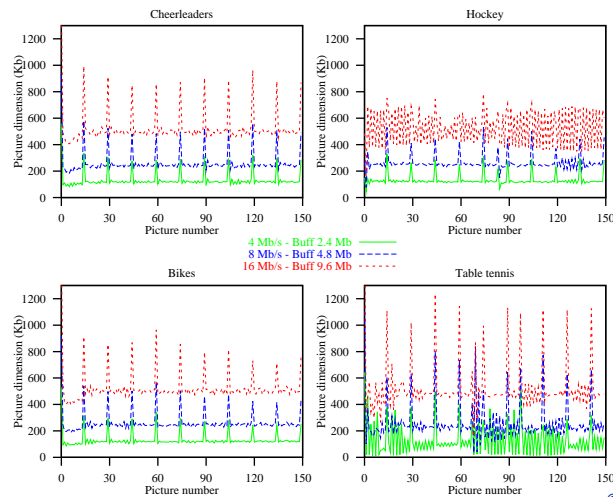
Natural MPEG Bit Rate



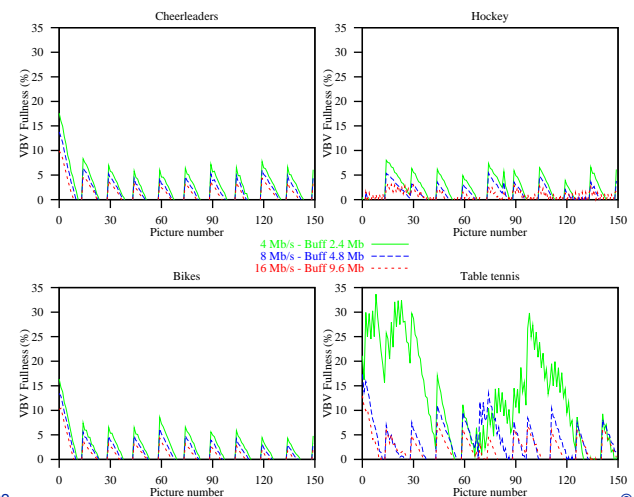
CBR MPEG Encoder



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

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

➤ visual quality of encoded video

High and uniform quality \Rightarrow 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 \Rightarrow large delay
Up to **GOP period** for static scenes

Road Map

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

Circuit Switching











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

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

Road Map

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	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ 	$\frac{F_r}{B} + S_w + P + P_d$ 	$\frac{F_r}{C} + \frac{P_s}{C} + E_r + P_d$  	$L \cdot T_f + P_d$ 
CBR MPEG	$S_c + P + D + P_d$	$S_c + P + D + P_d$   	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





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Packet Switching with Statistical Multiplexing

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













- $E_r \in [0, \Delta Q]$ 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 $\rightarrow S_c$ coding shaping delay 
- P_s packet size $\rightarrow D$ decoding delay 
- C link capacity $\rightarrow P_d$ presentation delay

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Road Map

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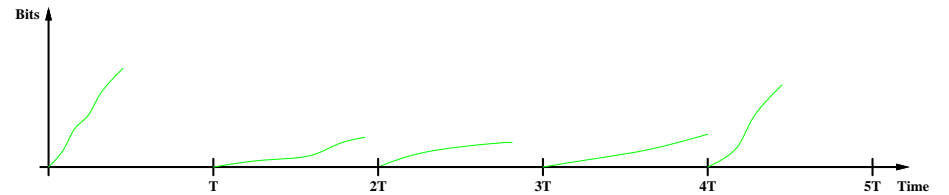
	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ 	$\frac{F_r}{B} + S_w + P + P_d$ 	$\frac{F_r}{C} + \frac{P_s}{C} + E_r + P_d$  	$L \cdot T_f + P_d$ 
CBR MPEG	$S_c + P + D + P_d$	$S_c + P + D + P_d$   	   	$S_c + L \cdot T_f + D + P_d$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

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VBR MPEG Encoding

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

$$C_M \leq T$$



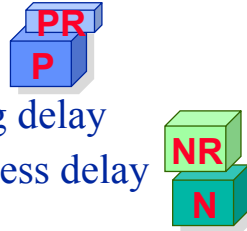
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Packet Switching with Statistical Multiplexing

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

- 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



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

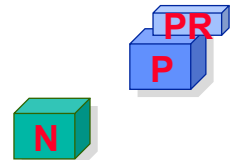
	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video	$\frac{F_r}{C} + P + P_d$ 	$\frac{F_r}{B} + S_w + P + P_d$ 	$\frac{F_r}{C} + S_n + \frac{P_s}{C} + E_r + P_d$ 	$L \cdot T_f + P_d$
CBR MPEG	$S_c + P + D + P_d$	$S_c + P + D + P_d$ 	$S_c + P + D + P_d$ 	$S_c + L \cdot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

Packet Switching with Time Driven Priority



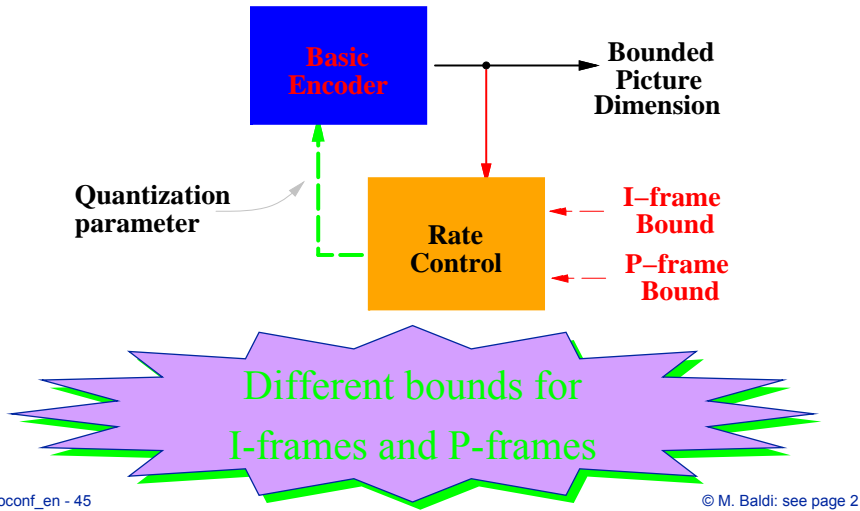
$$\Delta_{VBR}^{TDP} = C_M + L \cdot T_f + D + P_d$$

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



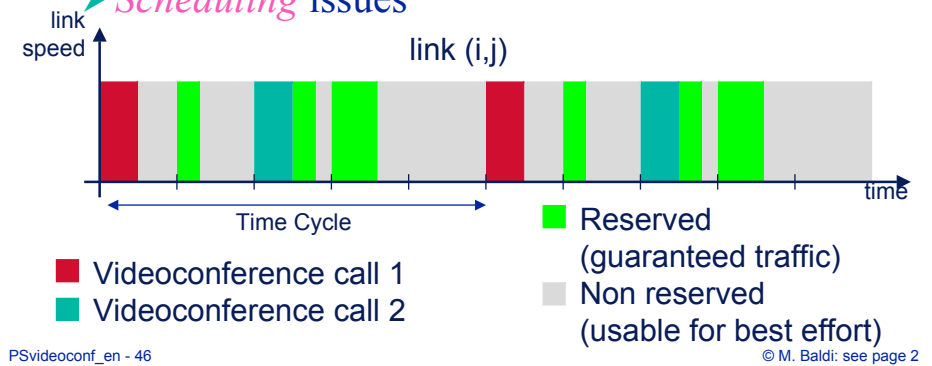
Picture dimension must be bound

Bounding Picture Dimension



Resource Allocation

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



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

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

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

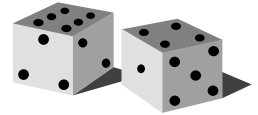
- N_r depends on scheduling
 - constant
 - fixed at reservation time

The Complete Picture

	Dedicated link	Circuit switching	Statistical multiplexing	Time driven priority
Raw video				
CBR MPEG				
VBR MPEG				

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