A

Video Experiments

We present in this appendix information pertaining to the video streaming experiments carried out in this work. We first present the video encoding structure chosen to compress sequences, then describe the latency-constrained video streaming process, and explain how we compute the peak-signal-to-noise-ratio (PSNR) which we use throughout the book as a video quality metric. Finally, we provide information on the 6 test sequences.

A.1 Video Streaming

A.1.1 Encoding Structures

The temporally layered scheme shown in Fig. A.1 is chosen to encode the video. For this open Group of Pictures (GOP), the first temporal layer is composed of I frames. The second temporal layer is composed of P frames. We restrict P frames to use as a reference the P frame or I frame preceding them in display order, as illustrated in the figure. The last layer is composed of B frames. We restrict the B frames to use as reference their two neighboring P frames or I frames[1]. This ensures good error resilience properties and allows to easily scale down the frame rate by 2 or even 4 if needed.

Fig. A.1. Encoding structure used for video streaming experiments with periodic I pictures. GOP length = 16

Table A.1 shows the other H.264 coding parameters chosen to generate the compressed sequences.

[1] Please note that these restrictions are not dictated by the H.264 standard.

Table A.1. H.264 encoding parameters

Hadamard transform	on
Search range	16 pixels
Number of reference frames	5
Hierarchical B frames	off
Entropy coding	CAVLC
Loop filter	on
Slices per picture	1
Rate-distortion optimization	on
Rate control	off

A.1.2 Latency-Constrained Video Streaming

In the video streaming experiments presented in this work, compressed video packets are made available at a sender, at a given time and need to be decoded shortly after at the receiver. Figure A.2, illustrates this process for the encoding structure shown in Fig. A.1.

As illustrated, the playout deadline is defined by the time between which the first frame of the sequence is made available at the sender and the time it is due at the decoder. Due to the dependencies between video frames, I frames and P frames are decoded 3 time slots before they are displayed. For the first frame of the sequence and for the B frames, the display and decoding times are identical.

A.1.3 Error-Resilient Decoding

We denote by $s(x, y, t)$ the luminance component of the original video signal, sampled on a regular grid of X by Y pixels, and by F the number of frames of the sequence. In the experiments we present, the video is compressed by an H.264 encoder and transmitted over a packet erasure channel. We denote by s_{dec} the decoded signal, recovered by the receiver.

Due to losses or to delay, all the data necessary to decode perfectly Frame t may not be available by the playout deadline of this frame. In this case, the decoder applies previous frame concealment:

$$s_{dec}(x, y, t) = s_{dec}(x, y, t - 1) \tag{A.1}$$

Previous frame concealment continues until a frame is received and decoded with no errors. This results in "freezing" Frame $t - 1$ over this time interval. The same process is also used to decode the color components of the video signal.

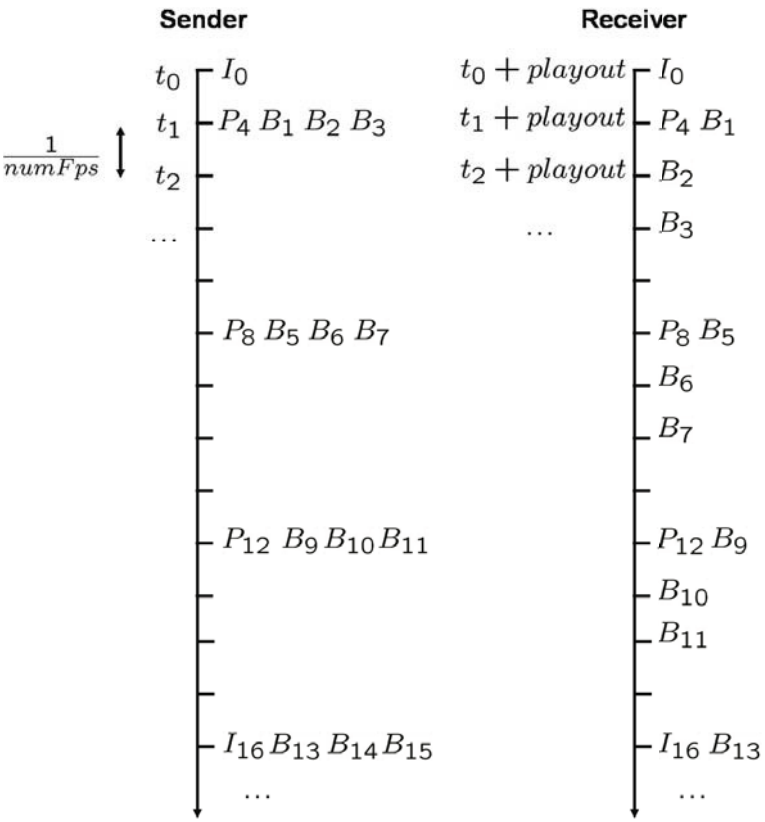

Fig. A.2. Illustration of latency-constrained video streaming. Two time axes are shown. The left axis shows the time at which frames are made available to the sender for transmission. The right axis shows when the different frames are due at the receiver. Frames are numbered, for clarity, in their display order. The first time slot at the sender and at the receiver is an exception, the rest of the process is periodic. The number of frames played by second is denoted by $numFps$. The playout deadline is denoted by $playout$.

A.1.4 Quality Metric

Throughout the book, we compute PSNR, as follows. First, the mean squared error of the luminance signal is computed, frame by frame:

$$MSE(t) = \frac{1}{XY} \sum_{x=1}^{X} \sum_{y=1}^{Y} (s(x, y, t) - s_{dec}(x, y, t))^2 \tag{A.2}$$

For each frame, the PSNR can then be derived from the MSE:

$$PSNR(t) = 10 \log_{10} \frac{255^2}{MSE(t)} \tag{A.3}$$

Finally, the average PSNR is computed by taking the average over all the frames of the sequence.

$$PSNR = \frac{1}{F} \sum_{t=1}^{F} PSNR(t) \tag{A.4}$$

In the literature, the PSNR is sometimes computed *after*, computing the average of the MSE for all frames. In practice, however, there is no difference between these two definitions [214].

To ensure stable results, we loop the sequences at least 40 times and consider long channel traces, rather than repeating the experiments over multiple channel realizations[2]. This is motivated by the fact that the channels we consider are throughput-limited and have time-varying bottleneck queues. Considering long experiments is necessary to evaluate the performance of the system in steady state.

[2] The length of the simulations is indicated in the related sections of Chapters 3 and 5.

A.2 Video Sequences

Throughout this book, 6 standard test sequences are used to collect experimental results. In this section we provide additional information on the video sequences, focusing, in particular on their rate-distortion characteristics.

A.2.1 Container

Fig. A.3. Example picture of the sequence *Container*.

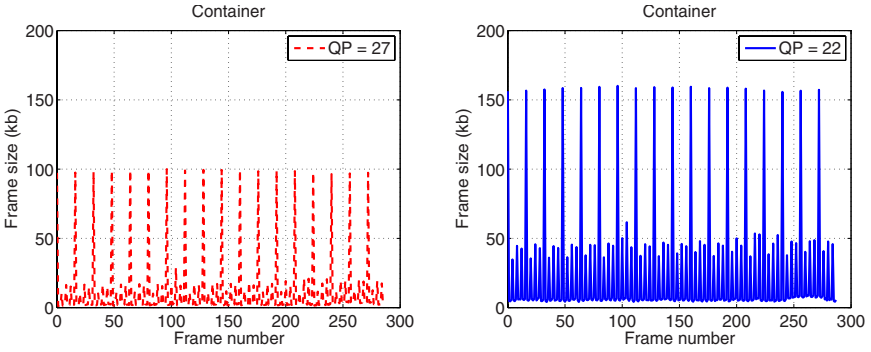

Fig. A.4. Left frame sizes for encoding rate 327 kb/s. Right: frame sizes for encoding rate 682 kb/s.

- **Sequence description:** video sequence captured with a fixed camera showing a container ship. The motion of the ship is slow and smooth. A small beating flag and a flight of birds, in the foreground, increase slightly the activity of the sequence.
- **Spatial resolution:** CIF, 288 x 352
- **Temporal resolution:** 30 frames per second
- **Number of frames:** 288 frames

Table A.2. Rate-distortion characteristics of the *Container* sequence, encoded with periodic I frames following the encoding structure shown in Fig. A.1.

QP	PSNR (dB)	Rate (kb/s)
20	41.92	896.64
21	41.25	782.61
22	40.64	681.92
23	39.87	581.98
24	39.22	502.59
25	38.71	442.45
26	37.87	372.62
27	37.24	327.01
28	36.62	283.42
29	35.97	244.13
30	35.38	214.72
31	34.85	191.19
32	34.19	164.65
33	33.66	145.02
34	33.04	128.30
35	32.40	112.16
36	31.83	98.18
37	31.32	88.68
38	30.61	77.39
39	30.08	69.80
40	29.52	62.07
41	28.91	55.34
42	28.31	49.29

A.2.2 Foreman

Fig. A.5. Example picture of the sequence *Foreman*.

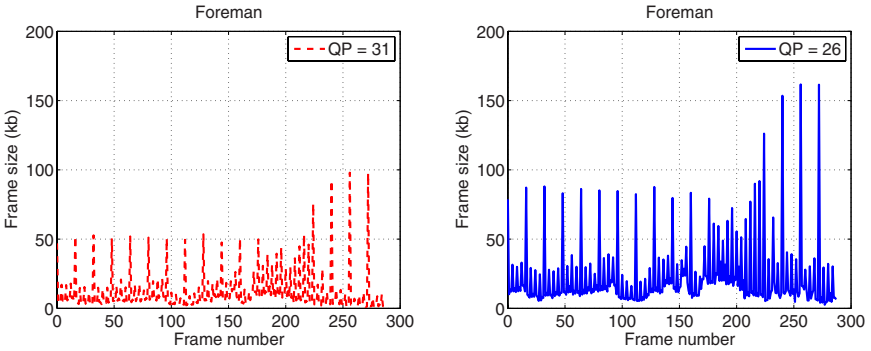

Fig. A.6. Left frame sizes for encoding rate 339 kb/s. Right: frame sizes for encoding rate 677 kb/s.

- **Sequence description:** sequence captured with a hand-held device, showing a talking head and a construction site. Motion is due to changes in facial expression and to camera motion which includes panning.
- **Spatial resolution:** CIF, 288 x 352
- **Temporal resolution:** 30 frames per second
- **Number of frames:** 288 frames

Table A.3. Rate-distortion characteristics of the *Foreman* sequence, encoded with periodic I frames following the encoding structure shown in Fig. A.1.

QP	PSNR (dB)	Rate (kb/s)
20	41.82	1739.98
21	41.15	1507.27
22	40.51	1293.22
23	39.78	1098.14
24	39.12	933.65
25	38.58	814.04
26	37.80	676.52
27	37.18	586.97
28	36.57	502.58
29	35.92	435.35
30	35.31	380.01
31	34.76	338.99
32	34.08	290.11
33	33.54	256.76
34	32.92	227.37
35	32.30	198.99
36	31.71	175.43
37	31.19	160.11
38	30.53	139.37
39	29.99	125.67
40	29.42	113.28
41	28.75	101.31
42	28.22	90.99

A.2.3 Mobile

Fig. A.7. Example picture of the sequence *Mobile*.

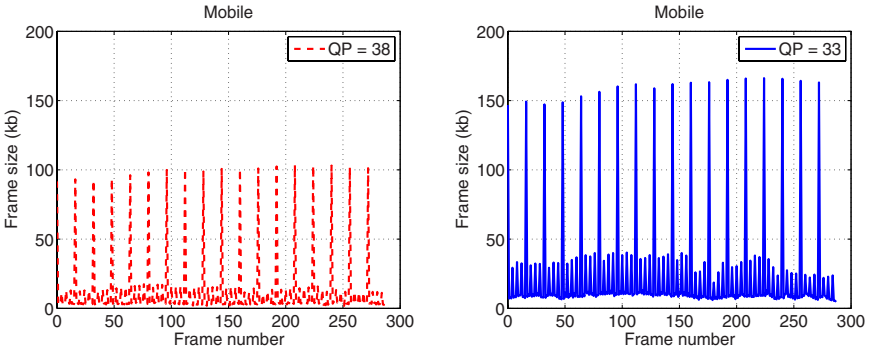

Fig. A.8. Left frame sizes for encoding rate 339 kb/s. Right: frame sizes for encoding rate 677 kb/s.

- **Sequence description:** active sequence with camera zoom and pan. Moving objects in the foreground and camera motion cause the background to be covered and uncovered.
- **Spatial resolution:** CIF, 288 x 352
- **Temporal resolution:** 30 frames per second
- **Number of frames:** 288 frames

Table A.4. Rate-distortion characteristics of the *Mobile* sequence, encoded with periodic I frames following the encoding structure shown in Fig. A.1.

QP	PSNR (dB)	Rate (kb/s)
20	40.83	4517.24
21	39.98	4045.62
22	39.16	3612.61
23	38.22	3146.58
24	37.32	2746.84
25	36.60	2442.04
26	35.58	2055.70
27	34.76	1783.24
28	33.93	1518.26
29	33.03	1271.54
30	32.23	1098.17
31	31.56	955.70
32	30.71	799.03
33	30.04	686.19
34	29.31	600.18
35	28.56	511.31
36	27.88	443.47
37	27.30	400.08
38	26.55	342.11
39	25.92	305.98
40	25.28	267.12
41	24.57	237.07
42	23.94	207.83

A.2.4 Mother & Daughter

Fig. A.9. Example picture of the sequence *Mother & Daughter*.

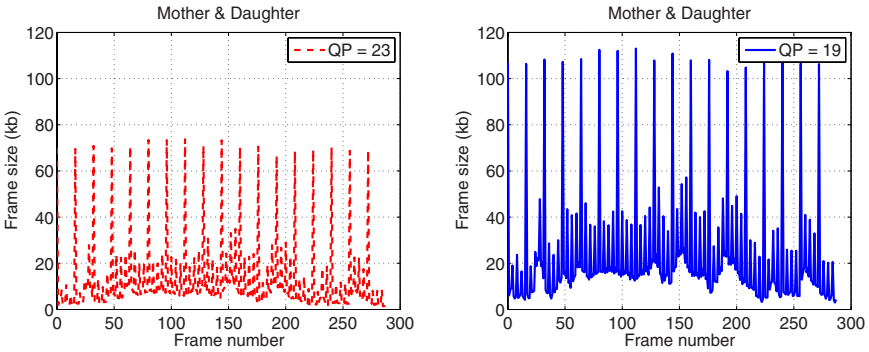

Fig. A.10. Left frame sizes for encoding rate 368 kb/s. Right: frame sizes for encoding rate 687 kb/s.

- **Sequence description:** video conference sequence captured with a fixed camera. There are two people in the foreground, one of which is talking, and a fixed background. The sequence displays limited motion mostly due to changes in facial expression and to arm motion of one of the characters.
- **Spatial resolution:** CIF, 288 x 352
- **Temporal resolution:** 30 frames per second
- **Number of frames:** 288 frames

Table A.5. Rate-distortion characteristics of the *Mother & Daughter* sequence, encoded with periodic I frames following the encoding structure shown in Fig. A.1.

QP	PSNR (dB)	Rate (kb/s)
19	44.48	686.54
20	43.94	566.96
21	43.42	493.74
22	42.89	426.66
23	42.28	367.70
24	41.74	318.67
25	41.29	281.55
26	40.54	239.32
27	39.97	211.81
28	39.37	184.62
29	38.76	161.18
30	38.12	142.32
31	37.57	126.80
32	36.92	109.50
33	36.38	97.08
34	35.75	85.61
35	35.09	75.52
36	34.58	65.85
37	34.13	59.38
38	33.44	51.22
39	33.09	45.61
40	32.48	40.13
41	31.88	35.32
42	31.36	31.37

A.2.5 News

Fig. A.11. Example picture of the sequence *News*.

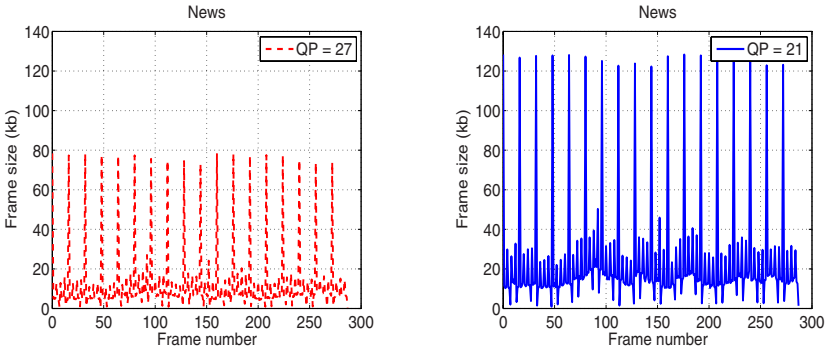

Fig. A.12. Left frame sizes for encoding rate 356 kb/s. Right: frame sizes for encoding rate 702 kb/s.

- **Sequence description:** typical news sequence, captured with a fixed camera, featuring an anchorman and an anchorwoman whose facial expression change moderately. Most of the activity of the sequence is caused by a large screen displaying an excerpt of a ballet with camera pan, in the background. The screen fills approximately one fifth of the picture.
- **Spatial resolution:** CIF, 288 x 352
- **Temporal resolution:** 30 frames per second
- **Number of frames:** 288 frames

Table A.6. Rate-distortion characteristics of the *News* sequence, encoded with periodic I frames following the encoding structure shown in Fig. A.1.

QP	PSNR (dB)	Rate (kb/s)
20	43.71	781.75
21	43.14	701.54
22	42.56	629.96
23	41.88	558.17
24	41.27	499.11
25	40.76	453.21
26	39.99	396.06
27	39.36	357.87
28	38.70	319.14
29	37.98	282.57
30	37.32	255.58
31	36.72	231.66
32	35.96	203.80
33	35.36	182.84
34	34.69	164.98
35	33.96	145.40
36	33.27	129.36
37	32.68	118.51
38	31.88	103.48
39	31.29	94.22
40	30.61	83.59
41	29.88	74.78
42	29.27	66.93

A.2.6 Salesman

Fig. A.13. Example picture of the sequence *Salesman*.

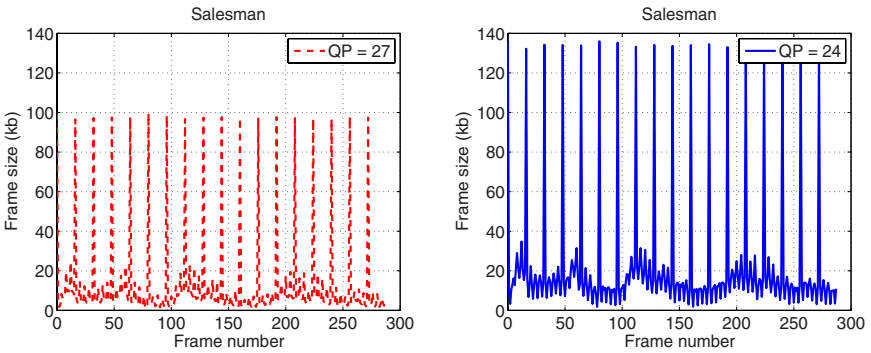

Fig. A.14. Left frame sizes for encoding rate 364 kb/s. Right: frame sizes for encoding rate 627 kb/s.

- **Description:** sequence captured with a fixed camera. The only motion is due to the limited motion of the character in the foreground. The background is fixed.
- **Spatial resolution:** CIF, 288 x 352
- **Temporal resolution:** 30 frames per second
- **Number of frames:** 288 frames

Table A.7. Rate-distortion characteristics of the *Salesman* sequence, encoded with periodic I frames following the encoding structure shown in Fig. A.1.

QP	PSNR (dB)	Rate (kb/s)
20	41.25	1452.18
21	40.54	1176.61
22	39.90	967.55
23	39.18	770.83
24	38.58	626.91
25	38.06	524.45
26	37.38	427.17
27	36.79	364.28
28	36.23	311.00
29	35.63	265.20
30	35.06	233.44
31	34.53	207.62
32	33.87	178.64
33	33.35	158.38
34	32.72	139.84
35	32.07	121.71
36	31.48	106.83
37	30.99	97.23
38	30.29	84.23
39	29.76	75.59
40	29.14	66.22
41	28.52	57.71
42	27.96	50.64

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