# Traffic and Quality Characterization of Scalable Encoded Video: A Large-Scale Trace-Based Study Part 2: Statistical Analysis of Single-Layer Encoded Video *†

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**Abstract**

In this part we analyze the frame size and frame quality traces of the roughly 116 hours of single layer encoded video in our trace library. For the video encoded without rate control (i.e., the quantization parameters are fixed for the entire video) we find that the coefficient of variation and the frame (as well as the GoP) size peak-to-mean ratio increase with decreasing quality (i.e., increasing quantization parameters). The coefficient of variation and peak-to-mean ratio have a peak ("hump") at a medium quality level and then decrease as the video quality is further decreased. This result extends on earlier studies which considered a smaller range of quality levels and uncovered only the increasing trend for decreasing quality. One implication of this "hump" behavior is that video traces can not simply be scaled to simulate the traffic corresponding to higher (or lower) video quality and correspondingly higher (or lower) bit rate. In particular, downscaling the traces of high quality video to simulate low quality (low bit rate) video, e.g., for wireless video streaming studies, will result in smaller traffic variability than is present in actual low quality encoded video. Our scaling analysis of video encoded without rate control indicates that the encodings do generally have no multiscaling properties. Our encodings with the TM5 rate control quantify the trade off between smoother traffic at the expense of more variability in the video quality for the low quality video.

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# 1 Introduction

In this part we conduct a statistical analysis of the video traffic and the video quality for the single-layer encoded video. This statistical analysis is based on the terse traces containing the frame sizes and the qualities (PSNR values) of the luminance component.

# 2 Analysis of Video Traffic

Table 1 gives the compression ratios, the means ($\bar{X}$), the coefficients of variation ($CoV_X$), and the peak-to-mean ratios ($X_{\max}/\bar{X}$) of the frame sizes, as well as the corresponding bit rates. These statistical measures are defined formally in the Appendix of Part 1. Comparing encodings at different quality levels for video sequences of different genres, we observe that the compression ratio increases as the quantization parameter (for I, P, and B frames) increases from 4 (for high quality) to 30 (for low quality), as one would expect. The relative order of the compression ratios among the various encoded video sequences is maintained when we compare encodings of different quality levels. This is due to the fact that for a given quantization parameter, the compression ratio achieved depends only on the input video sequence, provided all other encoding parameters are the same. Interestingly, we observe that the ratio of the compression ratios achieved at different quantization levels for various video sequences tends to have roughly the same value. That is to say, that for any given video sequence, the ratio of the medium quality compression ratio to the high quality compression ratio is around 5.0; similarly, this ratio of compression ratios is around 9.0, for the compression ratio of the low quality encoding compared to the compression ratio of the high quality encoded video. In other words, the compressibility of the data appears to be constant for a video sequence, and by changing the quantization parameter, we change the compression of the data approximately by a constant factor.

Usually, animation sequences tend to have fewer moving objects in a scene than natural live motion films. The animation sequences encoded as part of our study, such as *Cinderella* and *Aladdin*, follow this trend and have a small number of moving objects in any given video scene. For any video encoding, one would expect to find, that the fewer moving objects in a scene — against a constant background — the larger the compression ratio. More moving objects would require more bits for encoding, which would lower the compression ratio. The animation sequences in our study, however, have lower compression ratios than the live motion videos.

This appears to be due to the tendency of animation videos to dramatize and exaggerate the content features found in natural videos. Animation videos tend to have more frequent scene

and lighting changes, and thus, less temporal correlation than natural videos. Also, animation sequences tend to have sharper edges, resulting in large high frequency DCT coefficients. We leave a quantitative study of these effects for future work.

We also find that the lecture sequences in our study achieve only low compression ratios for a given quality level. This was another interesting phenomenon. The typical lecture video scene consists of a professor interacting with students and with the blackboard. A scene from the lecture usually falls into one of three categories. In the first type of scene, the camera points at the students, watching them watch the professor, and taking notes. Relative to the other categories of scenes for a lecture video, this type of scene has a relatively high level of texture but has only little movement. In the second type of scene, the camera points at the blackboard (or whiteboard), watching the professor write. Finally, in the third type of scene, the camera points directly at the professor's head and shoulders giving a lecture to the class. Overall, the lecture videos have relatively little motion and little texture. Hence, we would expect large compression ratios.

After noticing that we were, in fact, only achieving low compression ratios for these sequences, compared to the other videos at a given quality level, we took a closer look at the raw video source. The source videos, in this case, came from a library collection for students to review their lectures at home. Each tape, a copy of the original source, is relatively low in quality compared to the other source tapes used in this study. We are in the process of obtaining, coding, and analyzing lecture videos from high quality (noise free) sources. Low quality source material means that there is quite a bit of noise in the raw video. This noise significantly increases the magnitudes of high frequency coefficients in the DCT transform domain, which in turn increases the number of bits required to encode the video. In other words, the noise in the source, although relatively trivial to a viewer of the video, is not trivial to the encoder. This does, however, represent a real world scenario. Future network video traffic will likely come from many sources, including high quality commercial broadcasts, as well as relatively low quality home-made video.

When rate control is employed, the compression ratios achieved are nearly constant for rates of 256 kbps and 128 kbps; at a rate of 64 kbps we observe some significant deviations in the compression ratios. This is because the employed software encoder does not allow for quantization parameters larger than 31. Therefore our low quality encodings with the quantization parameter settings (30, 30, 30) for (I, P, B) frames are about the lowest quality and lowest bit rate encodings that are feasible with the employed encoder. Note that the low quality encodings of *Citizen Kane*, *Silence of the Lambs*, *Star Wars IV*, *Star Wars V*, *The Firm* and the *Tonight Show w/o Comm* have mean bit rates below 64 kbps. For these videos

the encoder meets the 64 kbps target bit rate. The low quality encodings of the other videos have mean bit rates above 64 kbps. Since the rate control cannot increase the quantization parameter above 31, encoding these other videos with a target bit rate of 64 kbps gives mean bit rates that are approximately equal to the mean bit rates of their low quality encodings.

We observe from Table 1 that the coefficient of variation ($CoV_X$) and the peak-to-mean ratio ($X_{\max}/\bar{X}$) of frame sizes both increase as the quality of encoded video decreases, from high quality to medium quality, indicating that the video traffic becomes more bursty. As the quality decreases further from medium to low quality, the coefficient of variation and the peak-to-mean ratio decrease. The causes of this phenomenon and its implications on channel utilization and buffer requirements will be explored in future work. Very large values of $CoV_X$ and $X_{\max}/\bar{X}$ are observed when rate control is applied. This is because for a given target bit rate, the employed TM5 rate control algorithm allocates target bit rates to each of the frame types (I, P, and B) and thus provides effective rate control at the GoP time scale — with potentially large variations of the individual frame sizes. We also observe that a rate-controlled encoding gives a higher peak bit rate than a non-rate-controlled encoding for a given video sequence. As the target bit rate increases both $CoV_X$ and $X_{\max}/\bar{X}$ decrease, indicating that the video traffic becomes less bursty.

Finally, we observe that the mean frame sizes of the *Silence of the Lambs* encodings without rate control in CIF format are roughly four times larger than for the corresponding QCIF encodings. This is to be expected since the CIF format is twice the size of the QCIF format in both the horizontal and the vertical direction and has thus four times the area of the QCIF format. The coefficient of variation and the peak-to-mean ratio of the frame sizes of the CIF encodings follow the trends of the QCIF encodings.

Table 1: Overview of frame statistics of single-layer traces

| | | Compr. | Frame Size | | | Bit Rate | |
|---|---|---|---|---|---|---|---|
| | | ratio | Mean | $CoV_X$ | Peak/Mean | Mean | Peak |
| Enc. M. | Video | YUV:MP4 | $\bar{X}$ [kbyte] | $S_X/\bar{X}$ | $X_{\max}/\bar{X}$ | $\bar{X}/T$ [Mbps] | $X_{\max}/T$ [Mbps] |
| QCIF | *Citizen Kane* | 19.965 | 1.904 | 0.842 | 8.735 | 0.457 | 3.992 |
| H. Q. | *Die Hard I* | 13.721 | 2.771 | 0.518 | 4.675 | 0.665 | 3.108 |
| No R.C. | *Jurassic Park I* | 11.632 | 3.268 | 0.660 | 5.949 | 0.784 | 4.666 |
| | *Silence of the Lambs* | 20.208 | 1.881 | 0.774 | 8.721 | 0.451 | 3.937 |
| | *Star Wars IV* | 16.524 | 2.301 | 0.609 | 7.615 | 0.552 | 4.204 |
| | *Star Wars V* | 11.016 | 3.451 | 0.533 | 4.608 | 0.828 | 3.816 |
| | *The Firm* | 14.706 | 2.585 | 0.666 | 6.812 | 0.620 | 4.227 |
| | *Terminator I* | 12.959 | 2.934 | 0.624 | 8.318 | 0.704 | 5.856 |
| | *Total Recall* | 13.329 | 2.852 | 0.548 | 5.411 | 0.685 | 3.704 |
| | *Aladdin* | 6.934 | 5.483 | 0.403 | 4.115 | 1.316 | 5.414 |
| | *Cinderella* | 9.856 | 3.857 | 0.527 | 6.816 | 0.926 | 6.310 |
| | *Baseball with Comm* | 9.219 | 4.123 | 0.399 | 4.368 | 0.990 | 4.323 |
| | *Snowboard with Comm* | 8.076 | 4.707 | 0.477 | 5.494 | 1.130 | 6.207 |
| | *Oprah w/o Comm* | 6.784 | 5.604 | 0.395 | 2.993 | 1.345 | 4.025 |
| | *Tonight Show w/o Comm* | 13.868 | 2.741 | 0.881 | 7.230 | 0.658 | 4.757 |
| | *Lecture–Gupta* | 7.331 | 5.186 | 0.314 | 3.272 | 1.245 | 4.072 |
| | *Lecture–Reisslein* | 6.713 | 5.663 | 0.430 | 4.886 | 1.359 | 6.641 |

Table 1: *continued*

| Enc. M. | Video | Compr. ratio YUV:MP4 | Frame Size Mean $\bar{X}$ [kbyte] | Frame Size $CoV_X$ $S_X/\bar{X}$ | Frame Size Peak/Mean $X_{\max}/\bar{X}$ | Bit Rate Mean $\bar{X}/T$ [Mbps] | Bit Rate Peak $X_{\max}/T$ [Mbps] |
|---|---|---|---|---|---|---|---|
| QCIF | *Jurassic Park I* | 40.040 | 0.949 | 1.017 | 9.345 | 0.228 | 2.130 |
| H.–M.Q. | *Star Wars IV* | 62.028 | 0.613 | 1.037 | 16.303 | 0.147 | 2.398 |
| No R.C. | *The Firm* | 56.797 | 0.669 | 1.168 | 12.015 | 0.161 | 1.930 |
| | *Tonight Show w/o Comm* | 52.844 | 0.719 | 1.360 | 13.611 | 0.173 | 2.350 |
| QCIF | *Citizen Kane* | 96.556 | 0.394 | 1.786 | 21.350 | 0.094 | 2.017 |
| M.Q. | *Die Hard I* | 75.038 | 0.507 | 1.335 | 13.614 | 0.122 | 1.655 |
| No R.C. | *Jurassic Park I* | 64.456 | 0.590 | 1.562 | 15.044 | 0.142 | 2.130 |
| | *Silence of the Lambs* | 114.211 | 0.333 | 1.663 | 25.386 | 0.080 | 2.028 |
| | *Star Wars IV* | 91.976 | 0.413 | 1.488 | 24.175 | 0.099 | 2.398 |
| | *Star Wars V* | 73.775 | 0.515 | 1.493 | 13.914 | 0.124 | 1.721 |
| | *The Firm* | 88.192 | 0.431 | 1.724 | 17.784 | 0.103 | 1.840 |
| | *Terminator I* | 61.267 | 0.620 | 1.262 | 11.873 | 0.149 | 1.768 |
| | *Total Recall* | 75.298 | 0.505 | 1.400 | 13.088 | 0.121 | 1.586 |
| | *Aladdin* | 43.479 | 0.874 | 1.217 | 10.688 | 0.210 | 2.243 |
| | *Cinderella* | 59.663 | 0.637 | 1.336 | 17.708 | 0.153 | 2.708 |
| | *Baseball with Comm* | 63.021 | 0.603 | 1.285 | 12.846 | 0.145 | 1.860 |
| | *Snowboard with Comm* | 45.592 | 0.834 | 1.173 | 12.847 | 0.200 | 2.571 |
| | *Oprah w/o Comm* | 49.961 | 0.761 | 1.322 | 10.001 | 0.183 | 1.826 |
| | *Tonight Show w/o Comm* | 86.674 | 0.439 | 2.128 | 20.022 | 0.105 | 2.108 |
| | *Lecture–Gupta* | 50.257 | 0.756 | 1.398 | 12.218 | 0.182 | 2.218 |
| | *Lecture–Reisslein* | 47.219 | 0.805 | 1.376 | 12.741 | 0.193 | 2.462 |
| QCIF | *Jurassic Park I* | 116.295 | 0.327 | 1.085 | 11.466 | 0.078 | 0.900 |
| M.–L.Q. | *Star Wars IV* | 139.591 | 0.272 | 1.033 | 19.468 | 0.065 | 1.272 |
| No R.C. | *The Firm* | 145.542 | 0.261 | 1.159 | 12.358 | 0.063 | 0.775 |
| | *Tonight Show w/o Comm* | 164.978 | 0.230 | 1.547 | 18.461 | 0.055 | 1.021 |
| QCIF | *Citizen Kane* | 175.409 | 0.217 | 1.077 | 12.601 | 0.052 | 0.655 |
| L.Q. | *Die Hard I* | 129.899 | 0.293 | 0.844 | 9.147 | 0.070 | 0.642 |
| No R.C. | *Jurassic Park I* | 137.305 | 0.277 | 0.974 | 10.485 | 0.066 | 0.697 |
| | *Silence of the Lambs* | 177.651 | 0.214 | 0.873 | 13.356 | 0.051 | 0.686 |
| | *Star Wars IV* | 153.598 | 0.248 | 0.920 | 17.289 | 0.059 | 1.027 |
| | *Star Wars V* | 141.799 | 0.268 | 0.941 | 10.134 | 0.064 | 0.652 |
| | *The Firm* | 163.806 | 0.232 | 1.008 | 10.527 | 0.056 | 0.586 |
| | *Terminator I* | 116.748 | 0.326 | 0.842 | 10.610 | 0.078 | 0.829 |
| | *Total Recall* | 134.182 | 0.283 | 0.883 | 7.670 | 0.068 | 0.522 |
| | *Aladdin* | 100.523 | 0.378 | 0.916 | 8.702 | 0.091 | 0.790 |
| | *Cinderella* | 122.625 | 0.310 | 0.889 | 14.831 | 0.074 | 1.104 |
| | *Baseball with Comm* | 122.975 | 0.309 | 0.846 | 7.754 | 0.074 | 0.575 |
| | *Snowboard with Comm* | 97.017 | 0.392 | 0.820 | 8.662 | 0.094 | 0.815 |
| | *Oprah w/o Comm* | 133.957 | 0.284 | 0.959 | 8.351 | 0.068 | 0.569 |
| | *Tonight Show w/o Comm* | 196.206 | 0.194 | 1.374 | 17.228 | 0.047 | 0.801 |
| | *Lecture–Gupta* | 129.925 | 0.293 | 1.250 | 11.876 | 0.070 | 0.834 |
| | *Lecture–Reisslein* | 127.663 | 0.298 | 1.195 | 13.765 | 0.071 | 0.984 |
| QCIF | *Citizen Kane* | 142.259 | 0.267 | 1.328 | 64.435 | 0.064 | 4.133 |
| R.C. | *Die Hard I* | 131.009 | 0.290 | 0.833 | 12.203 | 0.070 | 0.850 |
| 64 kbps | *Jurassic Park I* | 137.581 | 0.276 | 0.973 | 64.310 | 0.066 | 4.265 |
| | *Silence of the Lambs* | 142.253 | 0.267 | 1.118 | 67.003 | 0.064 | 4.297 |
| | *Star Wars IV* | 141.355 | 0.269 | 1.086 | 69.354 | 0.065 | 4.476 |
| | *Star Wars V* | 137.533 | 0.276 | 1.055 | 82.720 | 0.066 | 5.488 |
| | *The Firm* | 142.255 | 0.267 | 1.148 | 48.197 | 0.064 | 3.091 |
| | *Terminator I* | 116.602 | 0.326 | 0.861 | 53.645 | 0.078 | 4.198 |
| | *Total Recall* | 133.182 | 0.285 | 0.970 | 66.766 | 0.069 | 4.574 |
| | *Aladdin* | 102.525 | 0.371 | 0.918 | 60.114 | 0.089 | 5.350 |
| | *Cinderella* | 123.850 | 0.307 | 0.874 | 22.362 | 0.074 | 1.647 |
| | *Baseball with Comm* | 123.813 | 0.307 | 0.844 | 11.793 | 0.074 | 0.869 |
| | *Snowboard with Comm* | 99.000 | 0.384 | 0.806 | 8.398 | 0.092 | 0.774 |
| | *Oprah w/o Comm* | 136.007 | 0.280 | 1.023 | 93.701 | 0.067 | 6.286 |
| | *Tonight Show w/o Comm* | 140.998 | 0.270 | 1.494 | 45.286 | 0.065 | 2.930 |
| | *Lecture–Gupta* | 133.741 | 0.284 | 1.237 | 27.532 | 0.068 | 1.878 |
| | *Lecture–Reisslein* | 125.820 | 0.302 | 1.113 | 13.057 | 0.073 | 0.947 |

Table 1: *continued*

| Enc. M. | Video | Compr. ratio YUV:MP4 | Frame Size Mean $\bar{X}$ [kbyte] | Frame Size $CoV_X$ $S_X/\bar{X}$ | Frame Size Peak/Mean $X_{\max}/\bar{X}$ | Bit Rate Mean $\bar{X}/T$ [Mbps] | Bit Rate Peak $X_{\max}/T$ [Mbps] |
|---|---|---|---|---|---|---|---|
| QCIF | *Citizen Kane* | 71.206 | 0.534 | 1.401 | 17.749 | 0.128 | 2.274 |
| R.C. | *Die Hard I* | 71.204 | 0.534 | 1.169 | 20.918 | 0.128 | 2.680 |
| 128 kbps | *Jurassic Park I* | 71.205 | 0.534 | 1.295 | 20.774 | 0.128 | 2.662 |
| | *Silence of the Lambs* | 71.206 | 0.534 | 1.117 | 33.430 | 0.128 | 4.284 |
| | *Star Wars IV* | 71.206 | 0.534 | 1.132 | 22.063 | 0.128 | 2.827 |
| | *Star Wars V* | 71.206 | 0.534 | 1.132 | 26.592 | 0.128 | 3.407 |
| | *The Firm* | 71.206 | 0.534 | 1.286 | 22.291 | 0.128 | 2.856 |
| | *Terminator I* | 71.086 | 0.535 | 1.130 | 31.122 | 0.128 | 3.995 |
| | *Total Recall* | 71.207 | 0.534 | 1.182 | 19.649 | 0.128 | 2.518 |
| | *Aladdin* | 71.206 | 0.534 | 1.066 | 50.883 | 0.128 | 6.520 |
| | *Cinderella* | 71.206 | 0.534 | 1.186 | 41.940 | 0.128 | 5.374 |
| | *Baseball with Comm* | 71.205 | 0.534 | 1.119 | 26.185 | 0.128 | 3.355 |
| | *Snowboard with Comm* | 71.207 | 0.534 | 1.077 | 39.932 | 0.128 | 5.117 |
| | *Oprah w/o Comm* | 71.206 | 0.534 | 1.211 | 15.679 | 0.128 | 2.009 |
| | *Tonight Show w/o Comm* | 71.206 | 0.534 | 1.358 | 20.366 | 0.128 | 2.610 |
| | *Lecture–Gupta* | 71.206 | 0.534 | 1.604 | 19.677 | 0.128 | 2.521 |
| | *Lecture–Reisslein* | 71.206 | 0.534 | 1.293 | 25.650 | 0.128 | 3.287 |
| QCIF | *Citizen Kane* | 35.622 | 1.067 | 1.102 | 11.164 | 0.256 | 2.859 |
| R.C | *Die Hard I* | 35.622 | 1.067 | 0.978 | 8.981 | 0.256 | 2.300 |
| 256 kbps | *Jurassic Park I* | 35.622 | 1.067 | 1.106 | 9.345 | 0.256 | 2.394 |
| | *Silence of the Lambs* | 35.622 | 1.067 | 0.904 | 8.006 | 0.256 | 2.051 |
| | *Star Wars IV* | 35.622 | 1.067 | 0.927 | 9.659 | 0.256 | 2.474 |
| | *Star Wars V* | 35.622 | 1.067 | 0.961 | 6.890 | 0.256 | 1.765 |
| | *The Firm* | 35.621 | 1.067 | 1.046 | 10.775 | 0.256 | 2.760 |
| | *Terminator I* | 35.622 | 1.067 | 1.009 | 11.874 | 0.256 | 3.041 |
| | *Total Recall* | 35.622 | 1.067 | 1.001 | 8.991 | 0.256 | 2.303 |
| | *Aladdin* | 35.622 | 1.067 | 1.005 | 13.086 | 0.256 | 3.352 |
| | *Cinderella* | 35.622 | 1.067 | 1.010 | 10.049 | 0.256 | 2.574 |
| | *Baseball with Comm* | 35.622 | 1.067 | 0.924 | 10.565 | 0.256 | 2.706 |
| | *Snowboard with Comm* | 35.622 | 1.067 | 0.950 | 9.911 | 0.256 | 2.538 |
| | *Oprah w/o Comm* | 35.622 | 1.067 | 0.987 | 8.445 | 0.256 | 2.163 |
| | *Tonight Show w/o Comm* | 35.622 | 1.067 | 1.081 | 8.479 | 0.256 | 2.172 |
| | *Lecture–Gupta* | 35.621 | 1.067 | 1.090 | 9.192 | 0.256 | 2.354 |
| | *Lecture–Reisslein* | 35.622 | 1.067 | 0.989 | 7.426 | 0.256 | 1.902 |
| CIF | *Silence of Lambs* | 22.735 | 6.688 | 0.742 | 8.271 | 1.605 | 13.277 |
| 040404. | *Terminator I* | 14.973 | 10.156 | 0.564 | 5.497 | 2.437 | 13.398 |
| No.R.C. | *Snowboard with Comm* | 9.908 | 15.348 | 0.402 | 4.455 | 3.684 | 16.411 |
| | *Oprah w/o Comm* | 7.890 | 19.274 | 0.311 | 3.355 | 4.626 | 15.521 |
| | *ParkingLot* | 8.528 | 17.832 | 0.450 | 4.150 | 4.280 | 17.760 |
| | *LectureHQ-Reisslein* | 23.689 | 6.419 | 0.553 | 6.263 | 1.541 | 9.649 |
| CIF | *Silence of Lambs* | 47.721 | 3.187 | 1.301 | 13.994 | 0.765 | 10.702 |
| 040608. | *Terminator I* | 28.203 | 5.392 | 0.923 | 7.762 | 1.294 | 10.044 |
| No.R.C. | *Snowboard with Comm* | 20.580 | 7.389 | 0.853 | 6.672 | 1.773 | 11.831 |
| | *Oprah w/o Comm* | 18.034 | 8.432 | 0.820 | 4.862 | 2.024 | 9.838 |
| | *ParkingLot* | 16.784 | 9.060 | 0.948 | 6.011 | 2.174 | 13.071 |
| | *LectureHQ-Reisslein* | 52.194 | 2.913 | 1.495 | 12.649 | 0.699 | 8.845 |
| CIF | *Silence of Lambs* | 71.161 | 2.137 | 1.345 | 16.123 | 0.513 | 8.269 |
| 060810. | *Terminator I* | 38.703 | 3.929 | 0.926 | 8.710 | 0.943 | 8.213 |
| No.R.C. | *Snowboard with Comm* | 30.103 | 5.051 | 0.869 | 7.965 | 1.212 | 9.657 |
| | *Oprah w/o Comm* | 28.609 | 5.315 | 0.856 | 5.533 | 1.276 | 7.058 |
| | *ParkingLot* | 24.594 | 6.183 | 0.966 | 6.995 | 1.484 | 10.380 |
| | *LectureHQ-Reisslein* | 79.795 | 1.906 | 1.618 | 14.382 | 0.457 | 6.578 |
| CIF | *Silence of Lambs* | 83.051 | 1.831 | 1.181 | 14.506 | 0.439 | 6.374 |
| 101010. | *Terminator I* | 43.964 | 3.459 | 0.806 | 8.754 | 0.830 | 7.267 |
| No.R.C. | *Snowboard with Comm* | 36.082 | 4.214 | 0.710 | 8.028 | 1.011 | 8.120 |
| | *Oprah w/o Comm* | 36.750 | 4.138 | 0.562 | 5.153 | 0.993 | 5.117 |
| | *ParkingLot* | 27.418 | 5.546 | 0.798 | 6.422 | 1.331 | 8.548 |
| | *LectureHQ-Reisslein* | 95.279 | 1.596 | 1.221 | 14.186 | 0.383 | 5.434 |
| CIF | *Silence of Lambs* | 116.402 | 1.306 | 1.326 | 18.782 | 0.314 | 5.889 |

Table 1: *continued*

| Enc. M. | Video | Compr. ratio YUV:MP4 | Frame Size Mean $\bar{X}$ [kbyte] | Frame Size $CoV_X$ $S_X/\bar{X}$ | Frame Size Peak/Mean $X_{\max}/\bar{X}$ | Bit Rate Mean $\bar{X}/T$ [Mbps] | Bit Rate Peak $X_{\max}/T$ [Mbps] |
|---|---|---|---|---|---|---|---|
| 101416. | *Terminator I* | 63.308 | 2.402 | 0.970 | 10.581 | 0.576 | 6.100 |
| No. R.C. | *Snowboard with Comm* | 57.047 | 2.666 | 1.025 | 9.906 | 0.640 | 6.337 |
| | *Oprah w/o Comm* | 62.375 | 2.438 | 0.995 | 7.373 | 0.585 | 4.314 |
| | *ParkingLot* | 44.575 | 3.411 | 1.246 | 8.888 | 0.819 | 7.277 |
| | *LectureHQ-Reisslein* | 141.644 | 1.074 | 1.915 | 17.302 | 0.258 | 4.458 |
| CIF | *Silence of Lambs* | 153.029 | 0.994 | 0.916 | 13.957 | 0.238 | 3.329 |
| 242424. | *Terminator I* | 92.405 | 1.646 | 0.790 | 11.693 | 0.395 | 4.618 |
| No. R.C. | *Snowboard with Comm* | 91.491 | 1.662 | 0.792 | 10.683 | 0.399 | 4.261 |
| | *Oprah w/o Comm* | 111.413 | 1.365 | 0.667 | 10.109 | 0.328 | 3.312 |
| | *ParkingLot* | 80.036 | 1.900 | 1.040 | 8.647 | 0.456 | 3.943 |
| | *LectureHQ-Reisslein* | 215.257 | 0.706 | 1.336 | 18.159 | 0.170 | 3.079 |
| CIF | *Silence of Lambs* | 160.877 | 0.945 | 0.774 | 13.009 | 0.227 | 2.951 |
| 303030. | *Terminator I* | 105.134 | 1.446 | 0.733 | 11.748 | 0.347 | 4.078 |
| No. R.C. | *Snowboard with Comm* | 106.709 | 1.425 | 0.735 | 10.766 | 0.342 | 3.682 |
| | *Oprah w/o Comm* | 131.487 | 1.156 | 0.619 | 10.545 | 0.278 | 2.927 |
| | *ParkingLot* | 99.389 | 1.530 | 1.007 | 9.193 | 0.367 | 3.376 |
| | *LectureHQ-Reisslein* | 231.406 | 0.657 | 1.156 | 17.327 | 0.158 | 2.733 |
| CIF | *Silence of Lambs* | 162.275 | 0.937 | 0.762 | 12.901 | 0.225 | 2.901 |
| R.C. | *Terminator I* | 106.532 | 1.427 | 0.724 | 11.583 | 0.343 | 3.968 |
| 64kbps. | *Snowboard with Comm* | 108.120 | 1.406 | 0.720 | 10.711 | 0.338 | 3.615 |
| | *Oprah w/o Comm* | 133.213 | 1.142 | 0.606 | 10.555 | 0.274 | 2.892 |
| | *ParkingLot* | 101.609 | 1.497 | 0.993 | 9.221 | 0.359 | 3.312 |
| | *LectureHQ-Reisslein* | 232.909 | 0.653 | 1.126 | 17.072 | 0.157 | 2.675 |
| CIF | *Silence of Lambs* | 162.251 | 0.937 | 0.763 | 12.899 | 0.225 | 2.901 |
| R.C. | *Terminator I* | 106.516 | 1.428 | 0.724 | 11.581 | 0.343 | 3.968 |
| 128kbps. | *Snowboard with Comm* | 108.115 | 1.407 | 0.720 | 10.710 | 0.338 | 3.615 |
| | *Oprah w/o Comm* | 133.204 | 1.142 | 0.607 | 10.555 | 0.274 | 2.892 |
| | *ParkingLot* | 101.606 | 1.497 | 0.993 | 9.221 | 0.359 | 3.312 |
| | *LectureHQ-Reisslein* | 232.885 | 0.653 | 1.126 | 17.065 | 0.157 | 2.674 |
| CIF | *Silence of Lambs* | 137.562 | 1.105 | 0.933 | 49.493 | 0.265 | 13.131 |
| R.C. | *Terminator I* | 106.253 | 1.431 | 0.722 | 11.552 | 0.343 | 3.968 |
| 256kbps. | *Snowboard with Comm* | 107.719 | 1.412 | 0.729 | 17.755 | 0.339 | 6.015 |
| | *Oprah w/o Comm* | 128.102 | 1.187 | 0.686 | 14.182 | 0.285 | 4.040 |
| | *ParkingLot* | 101.548 | 1.497 | 0.995 | 9.618 | 0.359 | 3.457 |
| | *LectureHQ-Reisslein* | 142.497 | 1.067 | 1.741 | 15.237 | 0.256 | 3.902 |
| CIF | *ParkingLot* | 71.228 | 2.135 | 1.612 | 28.175 | 0.512 | 14.436 |
| R.C. | *LectureHQ-Reisslein* | 71.264 | 2.134 | 1.210 | 9.465 | 0.512 | 4.847 |
| 512kbps | *Silence of the Lambs* | | | | | | |
| CIF | *ParkingLot* | 35.637 | 4.267 | 1.049 | 16.733 | 1.024 | 17.136 |
| R.C. | *LectureHQ-Reisslein* | 35.636 | 4.267 | 0.837 | 6.665 | 1.024 | 6.825 |
| 1024kbps | *Silence of the Lambs* | | | | | | |

Table 2 gives the means ($\bar{Y}$), the coefficients of variation ($CoV_Y$), and the peak-to-mean ratios of the GoP sizes ($Y_{\max}/\bar{Y}$), as well as the corresponding bit rates. We observe that the coefficient of variation and the peak-to-mean ratio for the GoP aggregation level (of 12 frames) are significantly smaller compared to the frame level considered in Table 1. The decrease in the coefficient of variation and the peak-to-mean ratio is more pronounced for the encodings with rate control. This is due to the effect of the TM5 rate control, which strives to meet the target bit rate at the end of each GoP. For the encodings without rate control, we observe again the phenomenon of first increasing and then decreasing coefficient of variation and peak-to-mean ratio for decreasing video quality.

Table 2: Overview of GoP statistics of single-layer traces

| | | GoP Size | | | Bit Rate | |
|---|---|---|---|---|---|---|
| | | Mean | $CoV_Y$ | Peak/Mean | Mean | Peak |
| Enc. M. | Video | $\bar{Y}$ [kbyte] | $S_Y/\bar{Y}$ | $Y_{\max}/\bar{Y}$ | $\bar{Y}/(GT)$ [Mbps] | $Y_{\max}/(GT)$ [Mbps] |
| QCIF | *Citizen Kane* | 22.849 | 0.558 | 4.778 | 0.457 | 2.183 |
| H.Q. | *Die Hard I* | 33.248 | 0.299 | 2.606 | 0.665 | 1.733 |
| No R.C. | *Jurassic Park I* | 39.217 | 0.458 | 4.613 | 0.784 | 3.618 |
| | *Silence of the Lambs* | 22.575 | 0.587 | 7.367 | 0.451 | 3.326 |
| | *Star Wars IV* | 27.607 | 0.383 | 5.058 | 0.552 | 2.793 |
| | *Star Wars V* | 41.413 | 0.389 | 2.690 | 0.828 | 2.228 |
| | *The Firm* | 31.021 | 0.451 | 4.229 | 0.620 | 2.624 |
| | *Terminator I* | 35.203 | 0.426 | 4.009 | 0.704 | 2.823 |
| | *Total Recall* | 34.225 | 0.339 | 3.185 | 0.685 | 2.180 |
| | *Aladdin* | 65.792 | 0.287 | 2.764 | 1.316 | 3.637 |
| | *Cinderella* | 46.284 | 0.387 | 5.129 | 0.926 | 4.747 |
| | *Baseball with Comm* | 49.482 | 0.284 | 2.713 | 0.990 | 2.684 |
| | *Snowboard with Comm* | 56.485 | 0.389 | 4.201 | 1.130 | 4.746 |
| | *Oprah w/o Comm* | 67.251 | 0.318 | 2.004 | 1.345 | 2.696 |
| | *Tonight Show w/o Comm* | 32.896 | 0.709 | 4.560 | 0.658 | 3.000 |
| | *Lecture–Gupta* | 62.232 | 0.225 | 2.036 | 1.245 | 2.534 |
| | *Lecture–Reisslein* | 67.960 | 0.383 | 2.026 | 1.359 | 2.754 |
| QCIF | *Jurassic Park I* | 11.393 | 0.583 | 6.391 | 0.228 | 1.456 |
| H.–M.Q. | *Star Wars IV* | 7.355 | 0.536 | 7.902 | 0.147 | 1.162 |
| No R.C. | *The Firm* | 8.032 | 0.658 | 6.087 | 0.161 | 0.978 |
| | *Tonight Show w/o Comm* | 8.633 | 0.803 | 6.634 | 0.173 | 1.145 |
| QCIF | *Citizen Kane* | 4.725 | 0.569 | 5.623 | 0.094 | 0.531 |
| M.Q. | *Die Hard I* | 6.079 | 0.438 | 3.642 | 0.122 | 0.443 |
| No R.C. | *Jurassic Park I* | 7.078 | 0.540 | 6.072 | 0.142 | 0.860 |
| | *Silence of the Lambs* | 3.994 | 0.729 | 12.268 | 0.080 | 0.980 |
| | *Star Wars IV* | 4.960 | 0.502 | 7.313 | 0.099 | 0.725 |
| | *Star Wars V* | 6.184 | 0.557 | 4.279 | 0.124 | 0.529 |
| | *The Firm* | 5.173 | 0.602 | 5.562 | 0.103 | 0.575 |
| | *Terminator I* | 7.446 | 0.511 | 5.280 | 0.149 | 0.786 |
| | *Total Recall* | 6.058 | 0.467 | 4.006 | 0.121 | 0.485 |
| | *Aladdin* | 10.492 | 0.507 | 4.502 | 0.210 | 0.945 |
| | *Cinderella* | 7.646 | 0.528 | 9.446 | 0.153 | 1.445 |
| | *Baseball with Comm* | 7.239 | 0.453 | 3.882 | 0.145 | 0.562 |
| | *Snowboard with Comm* | 10.006 | 0.479 | 6.087 | 0.200 | 1.218 |
| | *Oprah w/o Comm* | 9.131 | 0.376 | 3.594 | 0.183 | 0.656 |
| | *Tonight Show w/o Comm* | 5.263 | 0.770 | 6.453 | 0.105 | 0.679 |
| | *Lecture–Gupta* | 9.077 | 0.310 | 2.783 | 0.182 | 0.505 |
| | *Lecture–Reisslein* | 9.661 | 0.476 | 3.076 | 0.193 | 0.594 |
| QCIF | *Jurassic Park I* | 3.923 | 0.481 | 4.979 | 0.078 | 0.391 |
| M.–L.Q. | *Star Wars IV* | 3.268 | 0.447 | 6.148 | 0.065 | 0.402 |
| No R.C. | *The Firm* | 3.134 | 0.508 | 4.498 | 0.063 | 0.282 |
| | *Tonight Show w/o Comm* | 2.765 | 0.747 | 5.996 | 0.055 | 0.332 |
| QCIF | *Citizen Kane* | 2.601 | 0.422 | 3.768 | 0.052 | 0.196 |
| L.Q. | *Die Hard I* | 3.512 | 0.395 | 3.020 | 0.070 | 0.212 |
| No R.C. | *Jurassic Park I* | 3.322 | 0.421 | 3.937 | 0.066 | 0.262 |
| | *Silence of the Lambs* | 2.568 | 0.464 | 7.891 | 0.051 | 0.405 |
| | *Star Wars IV* | 2.970 | 0.394 | 5.115 | 0.059 | 0.304 |
| | *Star Wars V* | 3.217 | 0.435 | 3.559 | 0.064 | 0.229 |
| | *The Firm* | 2.785 | 0.433 | 3.510 | 0.056 | 0.196 |
| | *Terminator I* | 3.908 | 0.438 | 4.492 | 0.078 | 0.351 |
| | *Total Recall* | 3.400 | 0.414 | 3.218 | 0.068 | 0.219 |
| | *Aladdin* | 4.538 | 0.452 | 4.305 | 0.091 | 0.391 |
| | *Cinderella* | 3.720 | 0.438 | 8.350 | 0.074 | 0.621 |
| | *Baseball with Comm* | 3.710 | 0.410 | 3.794 | 0.074 | 0.282 |
| | *Snowboard with Comm* | 4.702 | 0.383 | 4.851 | 0.094 | 0.456 |
| | *Oprah w/o Comm* | 3.406 | 0.360 | 3.866 | 0.068 | 0.263 |
| | *Tonight Show w/o Comm* | 2.325 | 0.671 | 5.174 | 0.047 | 0.241 |
| | *Lecture–Gupta* | 3.511 | 0.240 | 2.867 | 0.070 | 0.201 |
| | *Lecture–Reisslein* | 3.573 | 0.407 | 3.644 | 0.071 | 0.260 |

Table 2: *continued*

| | | GoP Size | | | Bit Rate | |
|---|---|---|---|---|---|---|
| | | Mean | $CoV_Y$ | Peak/Mean | Mean | Peak |
| Enc. M. | Video | $\bar{Y}$ [kbyte] | $S_Y/\bar{Y}$ | $Y_{\max}/\bar{Y}$ | $\bar{Y}/(GT)$ [Mbps] | $Y_{\max}/(GT)$ [Mbps] |
| QCIF | *Citizen Kane* | 3.207 | 0.354 | 13.905 | 0.064 | 0.892 |
| R.C | *Die Hard I* | 3.482 | 0.389 | 2.991 | 0.070 | 0.208 |
| 64 kbps | *Jurassic Park I* | 3.316 | 0.405 | 6.199 | 0.066 | 0.411 |
| | *Silence of the Lambs* | 3.207 | 0.387 | 12.643 | 0.064 | 0.811 |
| | *Star Wars IV* | 3.227 | 0.421 | 17.842 | 0.065 | 1.152 |
| | *Star Wars V* | 3.317 | 0.460 | 13.627 | 0.066 | 0.904 |
| | *The Firm* | 3.207 | 0.370 | 7.914 | 0.064 | 0.508 |
| | *Terminator I* | 3.912 | 0.437 | 12.037 | 0.078 | 0.942 |
| | *Total Recall* | 3.425 | 0.459 | 18.510 | 0.069 | 1.268 |
| | *Aladdin* | 4.450 | 0.447 | 6.608 | 0.089 | 0.588 |
| | *Cinderella* | 3.683 | 0.427 | 8.056 | 0.074 | 0.594 |
| | *Baseball with Comm* | 3.685 | 0.398 | 3.747 | 0.074 | 0.276 |
| | *Snowboard with Comm* | 4.608 | 0.378 | 4.763 | 0.092 | 0.439 |
| | *Oprah w/o Comm* | 3.354 | 0.379 | 8.861 | 0.067 | 0.594 |
| | *Tonight Show w/o Comm* | 3.235 | 0.428 | 5.034 | 0.065 | 0.326 |
| | *Lecture–Gupta* | 3.411 | 0.238 | 4.833 | 0.068 | 0.330 |
| | *Lecture–Reisslein* | 3.626 | 0.334 | 3.368 | 0.073 | 0.244 |
| QCIF | *Citizen Kane* | 6.407 | 0.091 | 3.539 | 0.128 | 0.453 |
| R.C. | *Die Hard I* | 6.407 | 0.117 | 2.841 | 0.128 | 0.364 |
| 128 kbps | *Jurassic Park I* | 6.407 | 0.129 | 5.198 | 0.128 | 0.666 |
| | *Silence of the Lambs* | 6.407 | 0.103 | 5.678 | 0.128 | 0.728 |
| | *Star Wars IV* | 6.407 | 0.089 | 3.566 | 0.128 | 0.457 |
| | *Star Wars V* | 6.407 | 0.118 | 4.842 | 0.128 | 0.620 |
| | *The Firm* | 6.407 | 0.089 | 3.327 | 0.128 | 0.426 |
| | *Terminator I* | 6.417 | 0.165 | 4.181 | 0.128 | 0.537 |
| | *Total Recall* | 6.407 | 0.106 | 2.626 | 0.128 | 0.336 |
| | *Aladdin* | 6.407 | 0.277 | 9.691 | 0.128 | 1.242 |
| | *Cinderella* | 6.407 | 0.206 | 7.652 | 0.128 | 0.980 |
| | *Baseball with Comm* | 6.407 | 0.160 | 4.180 | 0.128 | 0.536 |
| | *Snowboard with Comm* | 6.407 | 0.238 | 6.087 | 0.128 | 0.780 |
| | *Oprah w/o Comm* | 6.407 | 0.091 | 2.562 | 0.128 | 0.328 |
| | *Tonight Show w/o Comm* | 6.407 | 0.107 | 3.457 | 0.128 | 0.443 |
| | *Lecture–Gupta* | 6.407 | 0.092 | 5.018 | 0.128 | 0.643 |
| | *Lecture–Reisslein* | 6.407 | 0.091 | 3.654 | 0.128 | 0.468 |
| QCIF | *Citizen Kane* | 12.806 | 0.043 | 1.727 | 0.256 | 0.442 |
| R.C. | *Die Hard I* | 12.807 | 0.034 | 1.410 | 0.256 | 0.361 |
| 256 kbps | *Jurassic Park I* | 12.807 | 0.039 | 1.529 | 0.256 | 0.392 |
| | *Silence of the Lambs* | 12.806 | 0.030 | 1.572 | 0.256 | 0.403 |
| | *Star Wars IV* | 12.807 | 0.031 | 1.423 | 0.256 | 0.364 |
| | *Star Wars V* | 12.807 | 0.035 | 1.409 | 0.256 | 0.361 |
| | *The Firm* | 12.807 | 0.034 | 1.395 | 0.256 | 0.357 |
| | *Terminator I* | 12.807 | 0.053 | 1.989 | 0.256 | 0.509 |
| | *Total Recall* | 12.807 | 0.036 | 1.444 | 0.256 | 0.370 |
| | *Aladdin* | 12.806 | 0.072 | 1.766 | 0.256 | 0.452 |
| | *Cinderella* | 12.806 | 0.063 | 2.387 | 0.256 | 0.611 |
| | *Baseball with Comm* | 12.807 | 0.038 | 1.491 | 0.256 | 0.382 |
| | *Snowboard with Comm* | 12.806 | 0.059 | 2.070 | 0.256 | 0.530 |
| | *Oprah w/o Comm* | 12.807 | 0.024 | 1.336 | 0.256 | 0.342 |
| | *Tonight Show w/o Comm* | 12.807 | 0.037 | 1.486 | 0.256 | 0.381 |
| | *Lecture–Gupta* | 12.807 | 0.041 | 1.312 | 0.256 | 0.336 |
| | *Lecture–Reisslein* | 12.807 | 0.030 | 1.309 | 0.256 | 0.335 |
| CIF | *Silence of the Lambs* | 80.261 | 0.620 | 6.290 | 1.605 | 10.096 |
| 040404. | *Terminator I* | 121.868 | 0.417 | 2.979 | 2.437 | 7.260 |
| No.R.C. | *Snowboard with Comm* | 184.176 | 0.334 | 2.759 | 3.684 | 10.163 |
| | *Oprah w/o Comm* | 231.292 | 0.264 | 1.785 | 4.626 | 8.257 |
| | *ParkingLot* | 213.985 | 0.345 | 3.227 | 4.280 | 13.812 |
| | *LectureHQ-Reisslein* | 77.029 | 0.221 | 2.893 | 1.541 | 4.456 |
| CIF | *Silence of the Lambs* | 38.238 | 0.753 | 8.159 | 0.765 | 6.240 |
| 040608. | *Terminator I* | 64.701 | 0.465 | 3.349 | 1.294 | 4.334 |

Table 2: *continued*

| | | GoP Size | | | Bit Rate | |
|---|---|---|---|---|---|---|
| | | Mean | $CoV_Y$ | Peak/Mean | Mean | Peak |
| Enc. M. | Video | $\bar{Y}$ [kbyte] | $S_Y/\bar{Y}$ | $Y_{\max}/\bar{Y}$ | $\bar{Y}/(GT)$ [Mbps] | $Y_{\max}/(GT)$ [Mbps] |
| No.R.C. | *Snowboard with Comm* | 88.666 | 0.413 | 3.525 | 1.773 | 6.251 |
| | *Oprah w/o Comm* | 101.183 | 0.294 | 2.107 | 2.024 | 4.264 |
| | *ParkingLot* | 108.722 | 0.448 | 4.049 | 2.174 | 8.804 |
| | *LectureHQ-Reisslein* | 34.961 | 0.259 | 3.429 | 0.699 | 2.397 |
| CIF | *Silence of the Lambs* | 25.643 | 0.873 | 9.594 | 0.513 | 4.920 |
| 060810. | *Terminator I* | 47.148 | 0.504 | 3.585 | 0.943 | 3.380 |
| No.R.C. | *Snowboard with Comm* | 60.617 | 0.472 | 4.063 | 1.212 | 4.926 |
| | *Oprah w/o Comm* | 63.782 | 0.318 | 2.340 | 1.276 | 2.984 |
| | *ParkingLot* | 74.197 | 0.517 | 4.756 | 1.484 | 7.058 |
| | *LectureHQ-Reisslein* | 22.868 | 0.295 | 3.799 | 0.457 | 1.737 |
| CIF | *Silence of the Lambs* | 21.972 | 0.914 | 10.163 | 0.439 | 4.466 |
| 101010. | *Terminator I* | 41.506 | 0.519 | 3.664 | 0.830 | 3.042 |
| No.R.C. | *Snowboard with Comm* | 50.573 | 0.524 | 4.402 | 1.011 | 4.453 |
| | *Oprah w/o Comm* | 49.654 | 0.339 | 2.570 | 0.993 | 2.552 |
| | *ParkingLot* | 66.554 | 0.538 | 4.844 | 1.331 | 6.448 |
| | *LectureHQ-Reisslein* | 19.152 | 0.311 | 3.931 | 0.383 | 1.506 |
| CIF | *Silence of the Lambs* | 15.676 | 0.835 | 9.653 | 0.314 | 3.026 |
| 101416. | *Terminator I* | 28.824 | 0.514 | 3.741 | 0.576 | 2.157 |
| No.R.C. | *Snowboard with Comm* | 31.987 | 0.538 | 4.718 | 0.640 | 3.018 |
| | *Oprah w/o Comm* | 29.255 | 0.340 | 2.857 | 0.585 | 1.671 |
| | *ParkingLot* | 40.937 | 0.572 | 5.447 | 0.819 | 4.459 |
| | *LectureHQ-Reisslein* | 12.883 | 0.291 | 3.953 | 0.258 | 1.019 |
| CIF | *Silence of the Lambs* | 11.924 | 0.651 | 7.654 | 0.238 | 1.825 |
| 242424. | *Terminator I* | 19.747 | 0.479 | 3.580 | 0.395 | 1.414 |
| No.R.C. | *Snowboard with Comm* | 19.945 | 0.507 | 4.578 | 0.399 | 1.826 |
| | *Oprah w/o Comm* | 16.378 | 0.335 | 3.203 | 0.328 | 1.049 |
| | *ParkingLot* | 22.799 | 0.604 | 5.974 | 0.456 | 2.724 |
| | *LectureHQ-Reisslein* | 8.477 | 0.252 | 3.775 | 0.170 | 0.640 |
| CIF | *Silence of the Lambs* | 11.343 | 0.542 | 6.333 | 0.227 | 1.437 |
| 303030 | *Terminator I* | 17.357 | 0.444 | 3.346 | 0.347 | 1.162 |
| No.R.C. | *Snowboard with Comm* | 17.100 | 0.463 | 4.293 | 0.342 | 1.468 |
| | *Oprah w/o Comm* | 13.878 | 0.310 | 3.092 | 0.278 | 0.858 |
| | *ParkingLot* | 18.360 | 0.569 | 5.823 | 0.367 | 2.138 |
| | *LectureHQ-Reisslein* | 7.886 | 0.215 | 3.416 | 0.158 | 0.539 |
| CIF | *Silence of the Lambs* | 11.245 | 0.533 | 6.208 | 0.225 | 1.396 |
| R.C. | *Terminator I* | 17.129 | 0.439 | 3.322 | 0.343 | 1.138 |
| 64kbps | *Snowboard with Comm* | 16.877 | 0.453 | 4.228 | 0.338 | 1.427 |
| | *Oprah w/o Comm* | 13.698 | 0.305 | 3.057 | 0.274 | 0.837 |
| | *ParkingLot* | 17.959 | 0.562 | 5.777 | 0.359 | 2.075 |
| | *LectureHQ-Reisslein* | 7.835 | 0.210 | 3.386 | 0.157 | 0.531 |
| CIF | *Silence of the Lambs* | 11.247 | 0.533 | 6.207 | 0.225 | 1.396 |
| R.C. | *Terminator I* | 17.131 | 0.439 | 3.322 | 0.343 | 1.138 |
| 128kbps | *Snowboard with Comm* | 16.878 | 0.453 | 4.228 | 0.338 | 1.427 |
| | *Oprah w/o Comm* | 13.699 | 0.305 | 3.057 | 0.274 | 0.837 |
| | *ParkingLot* | 17.959 | 0.562 | 5.777 | 0.359 | 2.075 |
| | *LectureHQ-Reisslein* | 7.836 | 0.211 | 3.386 | 0.157 | 0.531 |
| CIF | *Silence of the Lambs* | 13.265 | 0.458 | 9.908 | 0.265 | 2.629 |
| R.C. | *Terminator I* | 17.174 | 0.436 | 3.313 | 0.343 | 1.138 |
| 256kbps | *Snowboard with Comm* | 16.940 | 0.449 | 4.213 | 0.339 | 1.427 |
| | *Oprah w/o Comm* | 14.245 | 0.275 | 6.002 | 0.285 | 1.710 |
| | *ParkingLot* | 17.969 | 0.562 | 5.774 | 0.359 | 2.075 |
| | *LectureHQ-Reisslein* | 12.806 | 0.101 | 2.280 | 0.256 | 0.584 |
| CIF | *ParkingLot* | 25.619 | 0.393 | 4.114 | 0.512 | 2.108 |
| R.C. | *LectureHQ-Reisslein* | 25.606 | 0.027 | 1.408 | 0.512 | 0.721 |
| 512kbps | *Silence of the Lambs* | | | | | |
| CIF | *ParkingLot* | 51.205 | 0.052 | 2.609 | 1.024 | 2.671 |
| R.C. | *LectureHQ-Reisslein* | 51.205 | 0.017 | 1.163 | 1.024 | 1.191 |
| 1024kbps | *Silence of the Lambs* | | | | | |

In the following we provide plots to illustrate the statistical properties of the following three single-layer encodings: (a) *Star Wars IV* encoded at high quality without rate control, (b) *Jurassic Park I* encoded at medium quality without rate control, (c) *Silence of the Lambs* encoded at low quality without rate control, (d) *Star Wars IV* encoded with rate control at a target bit rate of 256 kbps, (e) *Jurassic Park I* encoded with rate control at a target bit rate of 128 kbps, and (f) *Silence of the Lambs* encoded with rate control at a target bit rate of 64 kbps.

Figure 1 gives the frame sizes $X_n$ (in bits) as a function of the frame number $n$. *Star Wars IV* encoded at high quality has relatively smooth traces whereas *Jurassic Park I* and *Silence of the Lambs* have large variations. In all of the frame size plots, we observe that there are certain regions where the traffic activity is smooth; these regions correspond to distinct scenes of the video sequence. Encodings with rate control are more bursty at the frame time scale. For the larger GoP time scale (aggregation levels), these variations mostly die out, see Figure 2. From plots of the frame size traces at different aggregation levels, not shown here because of space constraints, we have observed that the burstiness of the videos without rate control does not die out even at very large aggregation levels. This indicates the presence of long range dependencies in the video traffic.

Figure 3 gives the histograms of the frame size $X_n$. We observe that encodings with rate control have narrower histograms than encodings without rate control. However, the histograms of the encodings with rate control have double peaks, indicating that the frames typically have one of two sizes. Due to the double peaks, the coefficient of variation of frame sizes is typically larger for encodings with rate control, as observed in Table 1.

Figure 4 gives the histograms of the GoP sizes ($Y_n$). We observe that the encodings with rate control have distinctively narrower histograms than the encodings without rate control. In future work we will investigate the tails of these histograms and their implications on networks in detail.

Figure 5 gives the autocorrelation coefficient $\rho_X(k)$ of the frame sequence $X_n$, $n = 0, \ldots, N-1$, as a function of the lag $k$ (in frames). For the encodings without rate control, the frame size autocorrelation plots appear as a train of spikes superimposed on a slowly decaying curve. The larger spikes in the plots for lags $k$ that are multiples of 12 — the number of frames in a GoP — and the relatively smaller spikes for lags $k$ that are multiples of 3 are explained in the following ways. With $k$ a multiple of 12, the relatively large I frames are correlated with each other, as are the P frames, resulting in the relatively very large I-I/P-P spikes in the autocorrelation. With $k$ a multiple of 3, on the other hand, I and P frames are correlated with each other, resulting in moderately large I-P spikes in the autocorrelation. For other values of $k$, I

and P frames are correlated with B frames, resulting in relatively small autocorrelation. We also observe from the plots that the relative difference between the very large I-I/P-P spikes and the moderately large I-P spikes is quite large for high quality encodings, small for medium quality encodings, and moderate for low quality encodings.

Figure 6 gives the autocorrelation coefficient $\rho_Y(k)$ of the GoP size sequence $Y_m$, $m = 0, \ldots, N/G - 1$, as a function of the lag $k$ (in GoPs). The autocorrelation function of the GoP size of the medium quality *Jurassic Park I* encoding is smooth and decreases roughly exponentially, indicating that this GoP process is approximately memoryless. The other two autocorrelation functions for video encoded without rate control do not have an exponential decay, indicating the presence of some long range dependencies. For encodings with a target bit rate of 256 kbps, the TM5 rate control gives nearly constant GoP sizes; see Table 2. These nearly constant GoP sizes result in very fast decay of the autocorrelation function. As the target bit rate decreases, the decay time increases, which may indicate that the effectiveness of the TM5 rate control algorithm decreases as the target bit rate decreases.

Table 3 gives the Hurst parameter $H$ determined with the R/S method (the first line of the given video and encoding mode) and the periodogram (the second line of the given video and encoding mode) as a function of the aggregation level $a$. Some R/S plots and periodogram plots for an aggregation level of $a = 12$ are given in Figures 8 and 9.

Table 3: Hurst parameters estimated from pox diagram of R/S and periodogram as a function of the aggregation level $a$.

| | | Aggregation level $a$ [frames] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Enc. M. | Video | 1 | 12 | 24 | 48 | 96 | 192 | 300 | 396 | 504 | 600 | 696 | 792 |
| QCIF | *Citizen Kane* | 0.952 | 0.921 | 0.920 | 0.909 | 0.898 | 0.889 | 0.888 | 0.898 | 0.899 | 0.850 | 0.838 | 0.803 |
| H.Q. | *Citizen Kane* | | 1.180 | 1.170 | 1.169 | 1.053 | 0.946 | 0.884 | 0.885 | 0.887 | 0.884 | 0.987 | 0.806 |
| No.R.C | *Die Hard I* | 0.873 | 0.793 | 0.774 | 0.769 | 0.758 | 0.743 | 0.721 | 0.672 | 0.659 | 0.650 | 0.616 | 0.642 |
| | *Die Hard I* | | 1.125 | 1.076 | 0.997 | 0.892 | 0.804 | 0.776 | 0.804 | 0.816 | 0.802 | 0.809 | 0.768 |
| | *Jurassic Park I* | 0.936 | 0.830 | 0.813 | 0.775 | 0.723 | 0.727 | 0.719 | 0.726 | 0.703 | 0.659 | 0.620 | 0.633 |
| | *Jurassic Park I* | | 1.207 | 1.207 | 1.115 | 1.068 | 0.991 | 0.951 | 0.934 | 0.951 | 0.930 | 0.827 | 0.848 |
| | *Silence of the Lambs* | 0.977 | 0.905 | 0.889 | 0.890 | 0.911 | 0.923 | 0.903 | 0.898 | 0.805 | 0.795 | 0.828 | 0.752 |
| | *Silence of the Lambs* | | 1.203 | 1.250 | 1.168 | 1.061 | 1.018 | 1.011 | 1.006 | 1.084 | 1.040 | 1.074 | 1.120 |
| | *Star Wars IV* | 0.927 | 0.857 | 0.849 | 0.839 | 0.826 | 0.815 | 0.837 | 0.834 | 0.851 | 0.857 | 0.881 | 0.874 |
| | *Star Wars IV* | | 1.123 | 1.109 | 1.061 | 1.028 | 0.965 | 0.961 | 1.005 | 0.960 | 1.014 | 0.909 | 1.029 |
| | *Star Wars V* | 0.958 | 0.875 | 0.849 | 0.853 | 0.834 | 0.826 | 0.801 | 0.789 | 0.846 | 0.780 | 0.817 | 0.752 |
| | *Star Wars V* | | 1.249 | 1.206 | 1.079 | 1.012 | 0.994 | 0.958 | 0.909 | 0.914 | 0.901 | 0.814 | 0.772 |
| | *The Firm* | 0.975 | 0.875 | 0.861 | 0.845 | 0.824 | 0.811 | 0.792 | 0.812 | 0.754 | 0.742 | 0.736 | 0.700 |
| | *The Firm* | | 1.168 | 1.196 | 1.144 | 1.096 | 1.085 | 1.033 | 1.057 | 0.990 | 1.043 | 1.026 | 1.009 |
| | *Terminator I* | 0.942 | 0.890 | 0.888 | 0.879 | 0.874 | 0.855 | 0.861 | 0.869 | 0.864 | 0.824 | 0.793 | 0.855 |
| | *Terminator I* | | 1.113 | 1.085 | 1.029 | 1.017 | 0.999 | 0.991 | 0.969 | 1.020 | 0.949 | 1.011 | 0.949 |
| | *Total Recall* | 0.920 | 0.870 | 0.865 | 0.848 | 0.853 | 0.836 | 0.830 | 0.821 | 0.840 | 0.823 | 0.822 | 0.829 |
| | *Total Recall* | | 1.135 | 1.121 | 1.053 | 0.995 | 0.993 | 0.930 | 0.985 | 0.876 | 0.918 | 0.866 | 0.895 |
| | *Aladdin* | 0.926 | 0.875 | 0.860 | 0.866 | 0.854 | 0.870 | 0.873 | 0.824 | 0.810 | 0.799 | 0.780 | 0.729 |
| | *Aladdin* | | 1.082 | 1.037 | 0.969 | 0.913 | 0.944 | 0.938 | 0.977 | 0.996 | 1.107 | 1.022 | 1.016 |
| | *Cinderella* | 0.916 | 0.848 | 0.835 | 0.845 | 0.856 | 0.857 | 0.880 | 0.864 | 0.838 | 0.866 | 0.821 | 0.880 |
| | *Cinderella* | | 1.136 | 1.079 | 1.000 | 0.968 | 0.983 | 0.995 | 1.023 | 1.034 | 1.018 | 1.053 | 0.973 |
| | *Baseball with Comm* | 0.933 | 0.825 | 0.819 | 0.798 | 0.810 | 0.838 | 0.855 | 0.876 | 0.810 | 0.812 | 0.876 | 0.858 |
| | *Baseball with Comm* | | 1.121 | 1.112 | 1.020 | 0.986 | 0.877 | 0.790 | 0.810 | 0.797 | 0.811 | 0.858 | 0.828 |
| | *Snowboard with Comm* | 0.897 | 0.786 | 0.765 | 0.742 | 0.713 | 0.691 | 0.695 | 0.699 | 0.730 | 0.739 | 0.668 | 0.740 |
| | *Snowboard with Comm* | | 1.199 | 1.115 | 0.930 | 0.935 | 0.868 | 0.804 | 0.754 | 0.730 | 0.787 | 0.660 | 0.746 |
| | *Oprah w/o Comm* | 0.983 | 0.875 | 0.864 | 0.858 | 0.882 | 0.887 | 0.982 | 0.921 | 0.986 | 0.988 | 0.898 | 0.901 |
| | *Oprah w/o Comm* | | 1.231 | 1.213 | 1.144 | 1.022 | 1.042 | 1.098 | 1.056 | 1.051 | 1.017 | 1.074 | 1.193 |
| | *Tonight Show w/o Comm* | 0.914 | 0.906 | 0.921 | 0.917 | 0.919 | 0.905 | 0.958 | 0.916 | 0.977 | 0.981 | 0.948 | 0.988 |
| | *Tonight Show w/o Comm* | | 1.180 | 1.228 | 1.245 | 1.245 | 1.226 | 1.227 | 1.265 | 1.328 | 1.286 | 1.321 | 1.281 |
| | *Lecture-Gupta* | 0.990 | 0.996 | 0.999 | 0.978 | 0.955 | 0.928 | 0.970 | 0.923 | 0.949 | 0.953 | 0.924 | 0.919 |
| | *Lecture-Gupta* | | 1.318 | 1.265 | 1.269 | 1.099 | 0.903 | 0.979 | 1.079 | 0.978 | 1.008 | 1.198 | 1.196 |
| | *Lecture-Reisslein* | 1.036 | 0.969 | 0.957 | 0.948 | 0.935 | 0.917 | 0.891 | 0.935 | 0.936 | 0.876 | 0.937 | 0.938 |
| | *Lecture-Reisslein* | | 1.339 | 1.305 | 1.226 | 1.195 | 1.138 | 1.161 | 1.208 | 1.246 | 1.288 | 1.303 | 1.320 |
| QCIF | *Jurassic Park I* | 0.907 | 0.814 | 0.788 | 0.750 | 0.697 | 0.701 | 0.686 | 0.690 | 0.660 | 0.623 | 0.584 | 0.585 |
| H.–M.Q. | *Jurassic Park I* | | 1.140 | 1.186 | 1.115 | 1.033 | 0.983 | 0.925 | 0.923 | 0.959 | 0.900 | 0.807 | 0.863 |
| No R.C. | *Star Wars IV* | 0.881 | 0.852 | 0.846 | 0.831 | 0.821 | 0.834 | 0.840 | 0.836 | 0.818 | 0.830 | 0.860 | 0.876 |

Table 3: *continued*

| Enc. M. | Video | Aggregation level $a$ [frames] 1 | 12 | 24 | 48 | 96 | 192 | 300 | 396 | 504 | 600 | 696 | 792 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Star Wars IV* | | 1.031 | 1.049 | 1.037 | 1.024 | 0.978 | 0.951 | 0.942 | 0.941 | 0.980 | 0.930 | 0.965 |
| | *The Firm* | 0.937 | 0.894 | 0.892 | 0.861 | 0.836 | 0.832 | 0.836 | 0.853 | 0.797 | 0.770 | 0.750 | 0.749 |
| | *The Firm* | | 1.061 | 1.113 | 1.104 | 1.074 | 1.112 | 1.045 | 1.069 | 1.072 | 1.096 | 1.039 | 1.125 |
| | *Tonight Show w/o Comm* | 0.825 | 0.870 | 0.868 | 0.870 | 0.879 | 0.877 | 0.952 | 0.896 | 0.938 | 0.982 | 0.952 | 1.003 |
| | *Tonight Show w/o Comm* | | 1.121 | 1.161 | 1.153 | 1.157 | 1.145 | 1.132 | 1.221 | 1.262 | 1.245 | 1.357 | 1.266 |
| QCIF | *Citizen Kane* | 0.840 | 0.906 | 0.912 | 0.898 | 0.883 | 0.887 | 0.897 | 0.880 | 0.888 | 0.861 | 0.832 | 0.788 |
| M.Q. | *Citizen Kane* | | 1.078 | 1.111 | 1.122 | 1.043 | 0.963 | 0.899 | 0.902 | 0.900 | 0.923 | 0.956 | 0.918 |
| No.R.C. | *Die Hard I* | 0.810 | 0.810 | 0.780 | 0.768 | 0.751 | 0.731 | 0.709 | 0.687 | 0.710 | 0.695 | 0.682 | 0.692 |
| | *Die Hard I* | | 1.036 | 1.058 | 0.984 | 0.921 | 0.864 | 0.802 | 0.908 | 0.818 | 0.737 | 0.777 | 0.774 |
| | *Jurassic Park I* | 0.840 | 0.811 | 0.786 | 0.752 | 0.699 | 0.703 | 0.684 | 0.679 | 0.662 | 0.631 | 0.587 | 0.578 |
| | *Jurassic Park I* | | 1.099 | 1.156 | 1.090 | 1.017 | 0.985 | 0.921 | 0.928 | 0.937 | 0.892 | 0.799 | 0.882 |
| | *Silence of the Lambs* | 0.858 | 0.912 | 0.895 | 0.889 | 0.881 | 0.888 | 0.887 | 0.853 | 0.831 | 0.806 | 0.808 | 0.776 |
| | *Silence of the Lambs* | | 1.053 | 1.131 | 1.106 | 1.034 | 1.008 | 1.030 | 1.006 | 1.034 | 1.089 | 1.061 | 1.123 |
| | *Star Wars IV* | 0.822 | 0.846 | 0.843 | 0.820 | 0.816 | 0.836 | 0.843 | 0.836 | 0.818 | 0.829 | 0.852 | 0.885 |
| | *Star Wars IV* | | 0.998 | 1.021 | 1.015 | 1.002 | 0.978 | 0.931 | 0.922 | 0.917 | 0.961 | 0.952 | 0.923 |
| | *Star Wars V* | 0.861 | 0.882 | 0.861 | 0.855 | 0.849 | 0.831 | 0.815 | 0.818 | 0.873 | 0.854 | 0.899 | 0.848 |
| | *Star Wars V* | | 1.113 | 1.118 | 1.040 | 0.984 | 0.974 | 0.951 | 0.917 | 0.871 | 0.927 | 0.849 | 0.896 |
| | *The Firm* | 0.868 | 0.891 | 0.881 | 0.855 | 0.832 | 0.826 | 0.844 | 0.858 | 0.802 | 0.778 | 0.752 | 0.753 |
| | *The Firm* | | 1.019 | 1.070 | 1.080 | 1.067 | 1.102 | 1.005 | 1.045 | 1.067 | 1.066 | 1.017 | 1.090 |
| | *Terminator I* | 0.881 | 0.903 | 0.903 | 0.885 | 0.866 | 0.858 | 0.873 | 0.871 | 0.876 | 0.878 | 0.866 | 0.906 |
| | *Terminator I* | | 1.044 | 1.068 | 1.032 | 1.030 | 0.969 | 0.998 | 1.010 | 0.991 | 0.998 | 1.057 | 0.969 |
| | *Total Recall* | 0.826 | 0.836 | 0.818 | 0.800 | 0.795 | 0.770 | 0.763 | 0.748 | 0.750 | 0.796 | 0.752 | 0.710 |
| | *Total Recall* | | 1.033 | 1.057 | 1.034 | 0.994 | 1.015 | 0.983 | 0.978 | 0.853 | 0.926 | 0.888 | 0.991 |
| | *Aladdin* | 0.861 | 0.881 | 0.866 | 0.875 | 0.875 | 0.898 | 0.911 | 0.841 | 0.869 | 0.855 | 0.796 | 0.774 |
| | *Aladdin* | | 1.020 | 0.994 | 0.953 | 0.922 | 0.985 | 0.947 | 0.991 | 1.017 | 1.044 | 1.037 | 1.044 |
| | *Cinderella* | 0.821 | 0.814 | 0.791 | 0.792 | 0.791 | 0.793 | 0.789 | 0.760 | 0.735 | 0.724 | 0.710 | 0.755 |
| | *Cinderella* | | 1.044 | 1.035 | 0.971 | 0.942 | 0.928 | 0.974 | 0.942 | 0.983 | 0.977 | 0.976 | 0.876 |
| | *Baseball with Comm* | 0.809 | 0.788 | 0.772 | 0.732 | 0.727 | 0.752 | 0.783 | 0.798 | 0.798 | 0.815 | 0.876 | 0.864 |
| | *Baseball with Comm* | | 1.037 | 1.036 | 1.019 | 0.982 | 0.819 | 0.749 | 0.758 | 0.749 | 0.719 | 0.797 | 0.726 |
| | *Snowboard with Comm* | 0.821 | 0.772 | 0.742 | 0.713 | 0.674 | 0.634 | 0.637 | 0.648 | 0.677 | 0.686 | 0.602 | 0.663 |
| | *Snowboard with Comm* | | 1.102 | 1.058 | 0.941 | 0.926 | 0.835 | 0.767 | 0.730 | 0.699 | 0.781 | 0.676 | 0.729 |
| | *Oprah w/o Comm* | 0.820 | 0.851 | 0.834 | 0.817 | 0.820 | 0.825 | 0.877 | 0.800 | 0.821 | 0.895 | 0.799 | 0.801 |
| | *Oprah w/o Comm* | | 1.095 | 1.107 | 1.079 | 1.013 | 1.003 | 1.013 | 1.002 | 0.990 | 0.984 | 0.972 | 1.035 |
| | *Tonight Show w/o Comm* | 0.761 | 0.865 | 0.862 | 0.868 | 0.879 | 0.880 | 0.958 | 0.904 | 0.961 | 1.006 | 0.946 | 1.004 |
| | *Tonight Show w/o Comm* | | 1.076 | 1.117 | 1.125 | 1.149 | 1.120 | 1.108 | 1.208 | 1.237 | 1.222 | 1.304 | 1.262 |
| | *Lecture-Gupta* | 0.787 | 0.987 | 0.970 | 0.939 | 0.919 | 0.887 | 0.904 | 0.856 | 0.899 | 0.907 | 0.884 | 0.880 |
| | *Lecture-Gupta* | | 1.144 | 1.183 | 1.219 | 1.138 | 0.973 | 0.999 | 0.989 | 0.883 | 0.900 | 1.189 | 1.066 |
| | *Lecture-Reisslein* | 0.870 | 0.966 | 0.958 | 0.940 | 0.922 | 0.926 | 0.904 | 0.955 | 0.960 | 0.889 | 0.960 | 0.981 |
| | *Lecture-Reisslein* | | 1.173 | 1.179 | 1.180 | 1.165 | 1.119 | 1.101 | 1.138 | 1.171 | 1.178 | 1.215 | 1.254 |
| QCIF | *Jurassic Park I* | 0.859 | 0.816 | 0.797 | 0.772 | 0.720 | 0.706 | 0.687 | 0.681 | 0.687 | 0.643 | 0.593 | 0.584 |
| M.–L.Q. | *Jurassic Park I* | | 1.059 | 1.118 | 1.045 | 0.970 | 0.938 | 0.892 | 0.898 | 0.894 | 0.856 | 0.790 | 0.827 |
| No.R.C. | *Star Wars IV* | 0.848 | 0.824 | 0.823 | 0.799 | 0.797 | 0.827 | 0.845 | 0.836 | 0.848 | 0.855 | 0.862 | 0.870 |
| | *Star Wars IV* | | 0.967 | 0.990 | 0.980 | 0.975 | 0.940 | 0.894 | 0.865 | 0.855 | 0.878 | 0.894 | 0.868 |
| | *The Firm* | 0.886 | 0.875 | 0.856 | 0.834 | 0.822 | 0.821 | 0.841 | 0.810 | 0.778 | 0.774 | 0.734 | 0.721 |
| | *The Firm* | | 0.966 | 1.023 | 1.030 | 1.002 | 0.997 | 0.923 | 0.996 | 0.980 | 1.036 | 0.974 | 0.996 |
| | *Tonight Show w/o Comm* | 0.776 | 0.852 | 0.856 | 0.845 | 0.866 | 0.848 | 0.918 | 0.882 | 0.934 | 0.952 | 0.888 | 0.956 |
| | *Tonight Show w/o Comm* | | 1.034 | 1.070 | 1.082 | 1.122 | 1.076 | 1.051 | 1.188 | 1.193 | 1.196 | 1.237 | 1.243 |
| QCIF | *Citizen Kane* | 0.855 | 0.875 | 0.864 | 0.841 | 0.835 | 0.825 | 0.858 | 0.852 | 0.881 | 0.870 | 0.844 | 0.795 |
| L.Q. | *Citizen Kane* | | 1.012 | 1.035 | 1.042 | 0.985 | 0.899 | 0.852 | 0.827 | 0.840 | 0.853 | 0.846 | 0.874 |
| No R.C. | *Die Hard I* | 0.850 | 0.822 | 0.798 | 0.777 | 0.755 | 0.745 | 0.745 | 0.742 | 0.763 | 0.748 | 0.724 | 0.687 |
| | *Die Hard I* | | 1.024 | 1.050 | 0.988 | 0.950 | 0.898 | 0.834 | 0.947 | 0.837 | 0.735 | 0.780 | 0.793 |
| | *Jurassic Park I* | 0.857 | 0.818 | 0.804 | 0.784 | 0.740 | 0.709 | 0.701 | 0.709 | 0.713 | 0.660 | 0.623 | 0.612 |
| | *Jurassic Park I* | | 1.041 | 1.109 | 1.030 | 0.950 | 0.923 | 0.892 | 0.871 | 0.875 | 0.829 | 0.776 | 0.795 |
| | *Silence of the Lambs* | 0.871 | 0.892 | 0.878 | 0.876 | 0.887 | 0.881 | 0.842 | 0.883 | 0.852 | 0.820 | 0.825 | 0.856 |
| | *Silence of the Lambs* | | 0.995 | 1.072 | 1.036 | 0.984 | 0.942 | 0.966 | 0.916 | 0.906 | 0.971 | 0.980 | 1.039 |
| | *Star Wars IV* | 0.845 | 0.810 | 0.811 | 0.787 | 0.786 | 0.815 | 0.836 | 0.832 | 0.834 | 0.868 | 0.872 | 0.864 |
| | *Star Wars IV* | | 0.959 | 0.982 | 0.971 | 0.979 | 0.931 | 0.874 | 0.848 | 0.832 | 0.865 | 0.890 | 0.831 |
| | *Star Wars V* | 0.863 | 0.848 | 0.831 | 0.827 | 0.837 | 0.823 | 0.826 | 0.859 | 0.909 | 0.877 | 0.965 | 0.946 |
| | *Star Wars V* | | 1.048 | 1.046 | 0.993 | 0.916 | 0.906 | 0.857 | 0.809 | 0.802 | 0.780 | 0.778 | 0.773 |
| | *The Firm* | 0.872 | 0.869 | 0.852 | 0.829 | 0.823 | 0.816 | 0.843 | 0.802 | 0.758 | 0.762 | 0.723 | 0.719 |
| | *The Firm* | | 0.946 | 0.998 | 1.010 | 0.971 | 0.961 | 0.891 | 1.008 | 0.936 | 1.038 | 0.955 | 0.964 |
| | *Terminator I* | 0.912 | 0.915 | 0.907 | 0.880 | 0.857 | 0.830 | 0.872 | 0.854 | 0.844 | 0.887 | 0.843 | 0.869 |
| | *Terminator I* | | 1.005 | 1.042 | 1.017 | 1.013 | 0.988 | 1.010 | 1.004 | 0.992 | 0.994 | 1.029 | 0.980 |
| | *Total Recall* | 0.861 | 0.834 | 0.805 | 0.795 | 0.768 | 0.746 | 0.739 | 0.728 | 0.720 | 0.735 | 0.750 | 0.666 |
| | *Total Recall* | | 0.988 | 1.013 | 0.998 | 0.969 | 0.985 | 1.023 | 0.984 | 0.872 | 0.955 | 0.939 | 1.002 |
| | *Aladdin* | 0.856 | 0.857 | 0.849 | 0.856 | 0.870 | 0.879 | 0.901 | 0.823 | 0.880 | 0.826 | 0.795 | 0.767 |
| | *Aladdin* | | 0.956 | 0.936 | 0.913 | 0.879 | 0.942 | 0.898 | 0.922 | 1.001 | 0.996 | 0.946 | 1.040 |
| | *Cinderella* | 0.815 | 0.784 | 0.766 | 0.775 | 0.765 | 0.772 | 0.749 | 0.722 | 0.704 | 0.696 | 0.687 | 0.724 |
| | *Cinderella* | | 0.969 | 0.963 | 0.921 | 0.901 | 0.896 | 0.935 | 0.901 | 0.964 | 0.964 | 0.940 | 0.889 |
| | *Baseball with Comm* | 0.812 | 0.761 | 0.737 | 0.682 | 0.664 | 0.665 | 0.707 | 0.708 | 0.702 | 0.737 | 0.770 | 0.746 |
| | *Baseball with Comm* | | 1.005 | 0.996 | 0.979 | 0.912 | 0.803 | 0.756 | 0.729 | 0.751 | 0.690 | 0.726 | 0.734 |
| | *Snowboard with Comm* | 0.813 | 0.763 | 0.729 | 0.694 | 0.648 | 0.612 | 0.565 | 0.597 | 0.595 | 0.582 | 0.544 | 0.545 |
| | *Snowboard with Comm* | | 1.010 | 0.980 | 0.898 | 0.881 | 0.788 | 0.708 | 0.658 | 0.653 | 0.602 | 0.611 | 0.662 |
| | *Oprah w/o Comm* | 0.844 | 0.860 | 0.836 | 0.800 | 0.782 | 0.769 | 0.737 | 0.668 | 0.650 | 0.702 | 0.681 | 0.599 |
| | *Oprah w/o Comm* | | 0.960 | 0.990 | 1.005 | 0.993 | 0.967 | 0.940 | 1.022 | 0.968 | 0.993 | 0.895 | 1.022 |
| | *Tonight Show w/o Comm* | 0.776 | 0.837 | 0.838 | 0.850 | 0.879 | 0.848 | 0.894 | 0.878 | 0.930 | 0.929 | 0.877 | 0.952 |
| | *Tonight Show w/o Comm* | | 1.013 | 1.053 | 1.065 | 1.111 | 1.076 | 1.054 | 1.176 | 1.189 | 1.183 | 1.228 | 1.234 |
| | *Lecture-Gupta* | 0.737 | 0.969 | 0.949 | 0.928 | 0.894 | 0.871 | 0.854 | 0.799 | 0.834 | 0.825 | 0.832 | 0.787 |
| | *Lecture-Gupta* | | 1.029 | 1.071 | 1.142 | 1.035 | 0.875 | 0.967 | 0.960 | 0.881 | 0.867 | 1.088 | 0.962 |
| | *Lecture-Reisslein* | 0.828 | 0.941 | 0.945 | 0.940 | 0.926 | 0.944 | 0.937 | 0.961 | 0.964 | 0.936 | 0.945 | 0.981 |
| | *Lecture-Reisslein* | | 1.085 | 1.080 | 1.130 | 1.083 | 1.076 | 1.077 | 1.114 | 1.142 | 1.130 | 1.281 | 1.222 |
| QCIF | *Citizen Kane* | 0.654 | 0.724 | 0.735 | 0.747 | 0.732 | 0.704 | 0.675 | 0.696 | 0.708 | 0.638 | 0.625 | 0.647 |
| R.C. | *Citizen Kane* | | 0.874 | 0.903 | 0.900 | 0.890 | 0.831 | 0.752 | 0.791 | 0.832 | 0.751 | 0.744 | 0.771 |

Table 3: *continued*

| | | Aggregation level $a$ [frames] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Enc. M. | Video | 1 | 12 | 24 | 48 | 96 | 192 | 300 | 396 | 504 | 600 | 696 | 792 |
| 64 kbps | *Die Hard I* | 0.850 | 0.822 | 0.791 | 0.771 | 0.757 | 0.751 | 0.738 | 0.745 | 0.776 | 0.761 | 0.739 | 0.686 |
| | *Die Hard I* | | 1.017 | 1.044 | 0.976 | 0.936 | 0.900 | 0.839 | 0.948 | 0.834 | 0.724 | 0.776 | 0.805 |
| | *Jurassic Park I* | 0.844 | 0.830 | 0.815 | 0.771 | 0.730 | 0.690 | 0.658 | 0.664 | 0.668 | 0.607 | 0.552 | 0.550 |
| | *Jurassic Park I* | | 1.025 | 1.081 | 1.009 | 0.947 | 0.883 | 0.870 | 0.840 | 0.839 | 0.842 | 0.731 | 0.821 |
| | *Silence of the Lambs* | 0.661 | 0.682 | 0.661 | 0.643 | 0.645 | 0.632 | 0.659 | 0.618 | 0.659 | 0.654 | 0.591 | 0.583 |
| | *Silence of the Lambs* | | 0.890 | 0.911 | 0.917 | 0.877 | 0.867 | 0.872 | 0.799 | 0.799 | 0.863 | 0.926 | 1.005 |
| | *Star Wars IV* | 0.709 | 0.657 | 0.656 | 0.624 | 0.616 | 0.631 | 0.625 | 0.635 | 0.674 | 0.659 | 0.563 | 0.640 |
| | *Star Wars IV* | | 0.871 | 0.900 | 0.872 | 0.869 | 0.834 | 0.831 | 0.773 | 0.773 | 0.792 | 0.810 | 0.793 |
| | *Star Wars V* | 0.814 | 0.833 | 0.826 | 0.810 | 0.850 | 0.850 | 0.835 | 0.867 | 0.908 | 0.876 | 0.963 | 0.917 |
| | *Star Wars V* | | 0.971 | 0.967 | 0.931 | 0.882 | 0.859 | 0.854 | 0.855 | 0.828 | 0.844 | 0.860 | 0.835 |
| | *The Firm* | 0.724 | 0.742 | 0.720 | 0.697 | 0.685 | 0.654 | 0.648 | 0.606 | 0.580 | 0.555 | 0.506 | 0.485 |
| | *The Firm* | | 0.857 | 0.915 | 0.951 | 0.893 | 0.900 | 0.805 | 0.881 | 0.808 | 0.848 | 0.808 | 0.810 |
| | *Terminator I* | 0.900 | 0.919 | 0.915 | 0.880 | 0.851 | 0.823 | 0.880 | 0.853 | 0.852 | 0.879 | 0.822 | 0.855 |
| | *Terminator I* | | 0.977 | 1.004 | 0.992 | 0.995 | 0.973 | 1.012 | 0.971 | 0.981 | 0.977 | 1.075 | 0.998 |
| | *Total Recall* | 0.839 | 0.819 | 0.793 | 0.795 | 0.770 | 0.739 | 0.732 | 0.716 | 0.709 | 0.710 | 0.714 | 0.635 |
| | *Total Recall* | | 0.966 | 0.992 | 0.996 | 0.982 | 0.966 | 0.979 | 0.921 | 0.850 | 0.905 | 0.927 | 1.062 |
| | *Aladdin* | 0.848 | 0.860 | 0.850 | 0.858 | 0.874 | 0.880 | 0.900 | 0.822 | 0.880 | 0.822 | 0.797 | 0.770 |
| | *Aladdin* | | 0.946 | 0.924 | 0.901 | 0.875 | 0.922 | 0.891 | 0.910 | 0.970 | 0.971 | 0.940 | 1.069 |
| | *Cinderella* | 0.808 | 0.776 | 0.756 | 0.760 | 0.748 | 0.756 | 0.746 | 0.715 | 0.697 | 0.697 | 0.688 | 0.728 |
| | *Cinderella* | | 0.944 | 0.928 | 0.909 | 0.893 | 0.875 | 0.907 | 0.875 | 0.957 | 0.942 | 0.911 | 0.902 |
| | *Baseball with Comm* | 0.809 | 0.776 | 0.755 | 0.692 | 0.669 | 0.665 | 0.716 | 0.715 | 0.712 | 0.757 | 0.785 | 0.771 |
| | *Baseball with Comm* | | 1.002 | 0.995 | 0.970 | 0.900 | 0.801 | 0.763 | 0.755 | 0.782 | 0.770 | 0.731 | 0.781 |
| | *Snowboard with Comm* | 0.812 | 0.765 | 0.732 | 0.698 | 0.650 | 0.616 | 0.566 | 0.603 | 0.598 | 0.584 | 0.550 | 0.558 |
| | *Snowboard with Comm* | | 1.005 | 0.983 | 0.896 | 0.881 | 0.787 | 0.703 | 0.656 | 0.647 | 0.591 | 0.598 | 0.652 |
| | *Oprah w/o Comm* | 0.832 | 0.844 | 0.826 | 0.789 | 0.775 | 0.768 | 0.738 | 0.670 | 0.644 | 0.697 | 0.674 | 0.588 |
| | *Oprah w/o Comm* | | 0.950 | 0.952 | 0.961 | 0.941 | 0.918 | 0.913 | 0.934 | 0.905 | 0.969 | 0.872 | 0.997 |
| | *Tonight Show w/o Comm* | 0.662 | 0.770 | 0.781 | 0.800 | 0.790 | 0.795 | 0.784 | 0.794 | 0.762 | 0.760 | 0.797 | 0.814 |
| | *Tonight Show w/o Comm* | | 0.895 | 0.985 | 1.069 | 1.100 | 1.088 | 1.035 | 1.082 | 0.898 | 1.113 | 1.009 | 0.803 |
| | *Lecture-Gupta* | 0.734 | 0.941 | 0.934 | 0.925 | 0.897 | 0.850 | 0.838 | 0.800 | 0.829 | 0.832 | 0.820 | 0.775 |
| | *Lecture-Gupta* | | 1.015 | 1.063 | 1.118 | 1.015 | 0.870 | 0.961 | 0.976 | 0.866 | 0.879 | 1.084 | 0.961 |
| | *Lecture-Reisslein* | 0.827 | 0.936 | 0.937 | 0.924 | 0.919 | 0.947 | 0.933 | 0.954 | 0.948 | 0.918 | 0.955 | 0.969 |
| | *Lecture-Reisslein* | | 1.010 | 1.037 | 1.115 | 1.075 | 1.074 | 1.074 | 1.048 | 1.049 | 1.060 | 1.177 | 1.133 |
| QCIF | *Citizen Kane* | 0.225 | 0.411 | 0.445 | 0.453 | 0.420 | 0.390 | 0.414 | 0.463 | 0.485 | 0.431 | 0.434 | 0.553 |
| R.C. | *Citizen Kane* | | 0.569 | 0.539 | 0.527 | 0.391 | 0.113 | -0.117 | -0.143 | -0.030 | -0.142 | -0.168 | -0.087 |
| 128 kbps | *Die Hard I* | 0.356 | 0.479 | 0.473 | 0.497 | 0.480 | 0.464 | 0.462 | 0.450 | 0.367 | 0.450 | 0.413 | 0.352 |
| | *Die Hard I* | | 0.585 | 0.542 | 0.522 | 0.383 | 0.118 | -0.047 | -0.052 | -0.109 | -0.203 | -0.160 | -0.305 |
| | *Jurassic Park I* | 0.430 | 0.617 | 0.645 | 0.634 | 0.580 | 0.530 | 0.509 | 0.490 | 0.487 | 0.478 | 0.490 | 0.386 |
| | *Jurassic Park I* | | 0.697 | 0.746 | 0.822 | 0.862 | 1.029 | 0.686 | 0.476 | 0.252 | 0.336 | 0.001 | -0.039 |
| | *Silence of the Lambs* | 0.258 | 0.433 | 0.436 | 0.428 | 0.421 | 0.503 | 0.523 | 0.594 | 0.553 | 0.566 | 0.487 | 0.599 |
| | *Silence of the Lambs* | | 0.723 | 0.835 | 0.972 | 1.039 | 0.951 | 0.631 | 0.329 | 0.198 | 0.127 | -0.032 | 0.004 |
| | *Star Wars IV* | 0.251 | 0.385 | 0.399 | 0.428 | 0.393 | 0.401 | 0.438 | 0.474 | 0.461 | 0.431 | 0.488 | 0.502 |
| | *Star Wars IV* | | 0.388 | 0.309 | 0.224 | 0.068 | 0.074 | -0.029 | 0.316 | 0.004 | -0.105 | 0.073 | 0.581 |
| | *Star Wars V* | 0.307 | 0.397 | 0.399 | 0.351 | 0.388 | 0.397 | 0.393 | 0.381 | 0.450 | 0.400 | 0.398 | 0.433 |
| | *Star Wars V* | | 0.524 | 0.401 | 0.266 | 0.199 | 0.069 | 0.077 | -0.004 | -0.313 | 0.025 | -0.089 | -0.158 |
| | *The Firm* | 0.284 | 0.445 | 0.432 | 0.458 | 0.446 | 0.428 | 0.493 | 0.491 | 0.508 | 0.519 | 0.547 | 0.500 |
| | *The Firm* | | 0.547 | 0.473 | 0.360 | 0.218 | -0.066 | -0.149 | -0.152 | -0.152 | -0.079 | -0.187 | -0.043 |
| | *Terminator I* | 0.445 | 0.562 | 0.567 | 0.559 | 0.528 | 0.568 | 0.489 | 0.552 | 0.495 | 0.454 | 0.483 | 0.471 |
| | *Terminator I* | | 0.704 | 0.674 | 0.640 | 0.641 | 0.576 | 0.648 | 0.521 | 0.412 | 0.489 | 0.272 | 0.312 |
| | *Total Recall* | 0.291 | 0.415 | 0.424 | 0.438 | 0.413 | 0.469 | 0.430 | 0.420 | 0.451 | 0.410 | 0.488 | 0.394 |
| | *Total Recall* | | 0.459 | 0.363 | 0.267 | 0.072 | -0.002 | -0.244 | -0.080 | -0.146 | -0.169 | -0.162 | -0.096 |
| | *Aladdin* | 0.524 | 0.556 | 0.538 | 0.532 | 0.520 | 0.499 | 0.548 | 0.438 | 0.515 | 0.521 | 0.485 | 0.487 |
| | *Aladdin* | | 0.739 | 0.695 | 0.668 | 0.720 | 0.721 | 0.674 | 0.766 | 0.657 | 0.655 | 0.752 | 0.773 |
| | *Cinderella* | 0.430 | 0.531 | 0.516 | 0.487 | 0.485 | 0.455 | 0.435 | 0.413 | 0.413 | 0.443 | 0.517 | 0.386 |
| | *Cinderella* | | 0.712 | 0.679 | 0.661 | 0.611 | 0.369 | 0.157 | 0.143 | -0.022 | -0.018 | -0.060 | -0.012 |
| | *Baseball with Comm* | 0.368 | 0.426 | 0.414 | 0.376 | 0.392 | 0.400 | 0.354 | 0.390 | 0.451 | 0.434 | 0.422 | 0.366 |
| | *Baseball with Comm* | | 0.595 | 0.493 | 0.388 | 0.457 | 0.180 | 0.044 | 0.042 | -0.131 | -0.307 | -0.048 | -0.267 |
| | *Snowboard with Comm* | 0.496 | 0.535 | 0.530 | 0.509 | 0.485 | 0.465 | 0.438 | 0.440 | 0.458 | 0.437 | 0.379 | 0.440 |
| | *Snowboard with Comm* | | 0.747 | 0.655 | 0.569 | 0.462 | 0.367 | 0.278 | 0.098 | 0.003 | -0.007 | -0.075 | -0.144 |
| | *Oprah w/o Comm* | 0.302 | 0.484 | 0.462 | 0.465 | 0.451 | 0.484 | 0.452 | 0.464 | 0.470 | 0.459 | 0.448 | 0.469 |
| | *Oprah w/o Comm* | | 0.567 | 0.523 | 0.418 | 0.172 | -0.060 | -0.174 | -0.136 | -0.084 | -0.213 | -0.190 | -0.106 |
| | *Tonight Show w/o Comm* | 0.324 | 0.514 | 0.513 | 0.529 | 0.459 | 0.434 | 0.412 | 0.537 | 0.284 | 0.394 | 0.423 | 0.417 |
| | *Tonight Show w/o Comm* | | 0.654 | 0.677 | 0.567 | 0.342 | 0.003 | -0.089 | -0.203 | -0.059 | -0.133 | -0.122 | -0.205 |
| | *Lecture-Gupta* | 0.216 | 0.414 | 0.402 | 0.396 | 0.414 | 0.466 | 0.547 | 0.644 | 0.706 | 0.664 | 0.616 | 0.551 |
| | *Lecture-Gupta* | | 0.676 | 0.607 | 0.764 | 0.857 | 0.892 | 0.376 | 0.438 | 0.110 | 0.287 | -0.004 | -0.128 |
| | *Lecture-Reisslein* | 0.309 | 0.551 | 0.553 | 0.539 | 0.483 | 0.469 | 0.439 | 0.473 | 0.510 | 0.504 | 0.409 | 0.557 |
| | *Lecture-Reisslein* | | 0.816 | 0.739 | 0.631 | 0.344 | 0.042 | -0.108 | -0.108 | -0.115 | -0.233 | -0.156 | -0.161 |
| QCIF | *Citizen Kane* | 0.160 | 0.249 | 0.278 | 0.284 | 0.289 | 0.310 | 0.276 | 0.424 | 0.409 | 0.547 | 0.641 | 0.796 |
| R.C. | *Citizen Kane* | | 0.016 | -0.044 | -0.123 | -0.142 | -0.104 | 0.006 | 0.055 | -0.041 | 0.114 | 0.138 | 0.094 |
| 256 kbps | *Die Hard I* | 0.153 | 0.246 | 0.214 | 0.220 | 0.236 | 0.259 | 0.383 | 0.414 | 0.465 | 0.547 | 0.819 | 0.665 |
| | *Die Hard I* | | -0.057 | -0.132 | -0.114 | -0.119 | -0.088 | 0.011 | 0.147 | 0.088 | 0.175 | 0.122 | 0.213 |
| | *Jurassic Park I* | 0.148 | 0.280 | 0.298 | 0.289 | 0.334 | 0.375 | 0.281 | 0.371 | 0.493 | 0.509 | 0.566 | 0.840 |
| | *Jurassic Park I* | | 0.008 | -0.077 | -0.087 | -0.102 | -0.078 | -0.012 | 0.053 | 0.140 | 0.127 | -0.040 | 0.228 |
| | *Silence of the Lambs* | 0.182 | 0.324 | 0.345 | 0.349 | 0.352 | 0.372 | 0.362 | 0.404 | 0.671 | 0.711 | 0.995 | 0.799 |
| | *Silence of the Lambs* | | 0.365 | 0.416 | 0.379 | -0.093 | -0.132 | 0.011 | 0.014 | -0.257 | 0.093 | 0.329 | 0.202 |
| | *Star Wars IV* | 0.180 | 0.316 | 0.256 | 0.273 | 0.265 | 0.343 | 0.263 | 0.509 | 0.509 | 0.459 | 1.082 | 0.882 |
| | *Star Wars IV* | | 0.162 | -0.057 | -0.091 | -0.054 | 0.019 | 0.029 | -0.048 | 0.066 | 0.081 | 0.194 | 0.155 |
| | *Star Wars V* | 0.167 | 0.257 | 0.289 | 0.303 | 0.287 | 0.307 | 0.324 | 0.397 | 0.463 | 0.574 | 0.636 | 0.579 |
| | *Star Wars V* | | 0.013 | -0.069 | -0.104 | -0.048 | 0.022 | 0.044 | -0.056 | 0.052 | 0.262 | 0.073 | -0.080 |
| | *The Firm* | 0.169 | 0.272 | 0.264 | 0.263 | 0.303 | 0.363 | 0.321 | 0.384 | 0.473 | 0.442 | 0.721 | 0.958 |
| | *The Firm* | | -0.033 | -0.122 | -0.157 | -0.109 | -0.041 | 0.017 | 0.076 | 0.092 | 0.175 | 0.025 | 0.181 |
| | *Terminator I* | 0.194 | 0.337 | 0.342 | 0.354 | 0.382 | 0.439 | 0.437 | 0.471 | 0.462 | 0.496 | 0.684 | 0.661 |
| | *Terminator I* | | 0.346 | 0.241 | 0.075 | 0.012 | -0.061 | 0.097 | -0.026 | -0.072 | -0.037 | 0.172 | -0.107 |
| | *Total Recall* | 0.168 | 0.286 | 0.240 | 0.253 | 0.269 | 0.307 | 0.403 | 0.381 | 0.386 | 0.494 | 0.612 | 0.910 |
| | *Total Recall* | | -0.039 | -0.147 | -0.138 | -0.014 | 0.028 | 0.038 | -0.037 | 0.022 | 0.080 | 0.119 | 0.269 |

Table 3: *continued*

| Enc. M. | Video | Aggregation level $a$ [frames] 1 | 12 | 24 | 48 | 96 | 192 | 300 | 396 | 504 | 600 | 696 | 792 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Aladdin* | 0.220 | 0.331 | 0.322 | 0.335 | 0.377 | 0.401 | 0.379 | 0.412 | 0.353 | 0.352 | 0.560 | 0.489 |
| | *Aladdin* | | 0.209 | -0.027 | -0.146 | -0.189 | -0.160 | -0.183 | -0.062 | -0.205 | -0.025 | 0.054 | -0.176 |
| | *Cinderella* | 0.271 | 0.449 | 0.456 | 0.439 | 0.448 | 0.462 | 0.275 | 0.426 | 0.455 | 0.456 | 0.527 | 0.604 |
| | *Cinderella* | | 0.603 | 0.525 | 0.221 | -0.085 | -0.174 | -0.058 | -0.199 | -0.232 | 0.067 | 0.075 | -0.272 |
| | *Baseball with Comm* | 0.182 | 0.308 | 0.306 | 0.300 | 0.289 | 0.276 | 0.416 | 0.381 | 0.570 | 0.520 | 0.601 | 0.693 |
| | *Baseball with Comm* | | 0.034 | -0.079 | -0.117 | -0.081 | -0.001 | -0.079 | -0.074 | 0.047 | 0.155 | 0.047 | 0.046 |
| | *Snowboard with Comm* | 0.251 | 0.366 | 0.353 | 0.392 | 0.366 | 0.416 | 0.342 | 0.392 | 0.330 | 0.408 | 0.543 | 0.699 |
| | *Snowboard with Comm* | | 0.273 | 0.075 | -0.096 | -0.141 | -0.125 | -0.031 | 0.023 | -0.035 | -0.123 | 0.079 | -0.142 |
| | *Oprah w/o Comm* | 0.131 | 0.307 | 0.307 | 0.237 | 0.300 | 0.294 | 0.359 | 0.460 | 0.458 | 0.605 | 1.047 | 0.471 |
| | *Oprah w/o Comm* | | 0.049 | -0.050 | -0.054 | -0.015 | 0.044 | 0.045 | -0.067 | 0.351 | 0.068 | 0.224 | 0.171 |
| | *Tonight Show w/o Comm* | 0.143 | 0.271 | 0.301 | 0.291 | 0.319 | 0.314 | 0.423 | 0.380 | 0.462 | 0.562 | 0.372 | 0.614 |
| | *Tonight Show w/o Comm* | | -0.020 | -0.114 | -0.121 | -0.140 | -0.005 | -0.048 | 0.062 | 0.273 | 0.162 | -0.038 | 0.110 |
| | *Lecture-Gupta* | 0.119 | 0.169 | 0.166 | 0.190 | 0.188 | 0.156 | 0.287 | 0.317 | 0.353 | 0.504 | 0.767 | 0.648 |
| | *Lecture-Gupta* | | -0.025 | -0.128 | -0.138 | -0.070 | -0.038 | -0.061 | 0.107 | -0.029 | 0.072 | 0.117 | 0.133 |
| | *Lecture-Reisslein* | 0.123 | 0.243 | 0.230 | 0.250 | 0.232 | 0.272 | 0.370 | 0.378 | 0.518 | 0.669 | 0.663 | 1.037 |
| | *Lecture-Reisslein* | | 0.009 | -0.045 | -0.093 | -0.045 | 0.040 | 0.110 | 0.112 | 0.246 | 0.255 | 0.257 | 0.063 |
| CIF | *Silence of the Lambs* | 0.990 | 0.929 | 0.904 | 0.913 | 0.932 | 0.959 | 0.922 | 0.925 | 0.821 | 0.850 | 0.893 | 0.805 |
| 040404. | *Silence of the Lambs* | | 1.135 | 1.209 | 1.130 | 1.032 | 1.049 | 1.119 | 1.065 | 1.130 | 1.047 | 1.065 | 1.177 |
| No.R.C. | *Terminator I* | 0.941 | 0.817 | 0.809 | 0.808 | 0.797 | 0.815 | 0.854 | 0.900 | 0.900 | 0.929 | 0.980 | 0.981 |
| | *Terminator I* | | 1.101 | 1.084 | 1.011 | 0.911 | 0.946 | 0.798 | 0.825 | 0.770 | 0.680 | 0.833 | 0.727 |
| | *Snowboard with Comm* | 0.889 | 0.726 | 0.688 | 0.645 | 0.598 | 0.588 | 0.597 | 0.557 | 0.574 | 0.537 | 0.514 | 0.537 |
| | *Snowboard with Comm* | | 1.170 | 1.065 | 0.804 | 0.785 | 0.793 | 0.637 | 0.502 | 0.569 | 0.634 | 0.460 | 0.475 |
| | *Oprah w/o Comm* | 0.986 | 0.879 | 0.866 | 0.859 | 0.866 | 0.876 | 0.899 | 0.857 | 0.856 | 0.948 | 0.788 | 0.870 |
| | *Oprah w/o Comm* | | 1.234 | 1.272 | 1.237 | 1.160 | 1.149 | 1.084 | 1.220 | 1.168 | 1.101 | 1.197 | 1.044 |
| | *ParkingLot* | 0.717 | 0.475 | 0.438 | 0.462 | 0.482 | 0.482 | 0.509 | 0.549 | 0.674 | 0.779 | 0.702 | 0.786 |
| | *ParkingLot* | | 0.965 | 0.737 | 0.608 | 0.471 | 0.534 | 0.373 | 0.327 | 0.323 | 0.409 | 0.533 | 0.430 |
| | *LectureHQ-Reisslein* | 0.812 | 0.860 | 0.853 | 0.826 | 0.822 | 0.797 | 0.778 | 0.807 | 0.792 | 0.785 | 0.741 | 0.739 |
| | *LectureHQ-Reisslein* | | 1.093 | 1.079 | 1.055 | 1.079 | 1.008 | 1.005 | 1.047 | 0.958 | 0.904 | 0.972 | 0.838 |
| CIF | *Silence of the Lambs* | 0.911 | 0.931 | 0.910 | 0.919 | 0.921 | 0.935 | 0.893 | 0.908 | 0.806 | 0.818 | 0.906 | 0.819 |
| 040608. | *Silence of the Lambs* | | 1.072 | 1.158 | 1.119 | 1.027 | 1.010 | 1.070 | 1.019 | 1.075 | 1.041 | 1.064 | 1.156 |
| No.R.C. | *Terminator I* | 0.883 | 0.802 | 0.792 | 0.784 | 0.772 | 0.790 | 0.838 | 0.872 | 0.881 | 0.924 | 0.969 | 0.995 |
| | *Terminator I* | | 1.069 | 1.063 | 0.994 | 0.898 | 0.929 | 0.782 | 0.824 | 0.719 | 0.630 | 0.783 | 0.665 |
| | *Snowboard with Comm* | 0.839 | 0.734 | 0.695 | 0.656 | 0.614 | 0.596 | 0.614 | 0.567 | 0.594 | 0.526 | 0.493 | 0.445 |
| | *Snowboard with Comm* | | 1.150 | 1.058 | 0.842 | 0.865 | 0.839 | 0.699 | 0.604 | 0.586 | 0.649 | 0.554 | 0.552 |
| | *Oprah w/o Comm* | 0.837 | 0.872 | 0.846 | 0.835 | 0.832 | 0.846 | 0.862 | 0.821 | 0.803 | 0.905 | 0.755 | 0.837 |
| | *Oprah w/o Comm* | | 1.160 | 1.224 | 1.221 | 1.122 | 1.110 | 1.034 | 1.141 | 1.096 | 1.032 | 1.120 | 0.974 |
| | *ParkingLot* | 0.651 | 0.437 | 0.398 | 0.419 | 0.461 | 0.478 | 0.504 | 0.550 | 0.663 | 0.759 | 0.675 | 0.756 |
| | *ParkingLot* | | 0.946 | 0.713 | 0.567 | 0.390 | 0.472 | 0.306 | 0.290 | 0.289 | 0.278 | 0.446 | 0.382 |
| | *LectureHQ-Reisslein* | 0.688 | 0.838 | 0.826 | 0.802 | 0.790 | 0.782 | 0.775 | 0.801 | 0.786 | 0.815 | 0.794 | 0.815 |
| | *LectureHQ-Reisslein* | | 1.061 | 1.024 | 0.989 | 0.994 | 0.919 | 0.908 | 0.911 | 0.829 | 0.806 | 0.843 | 0.707 |
| CIF | *Silence of the Lambs* | 0.924 | 0.930 | 0.910 | 0.914 | 0.910 | 0.916 | 0.880 | 0.891 | 0.781 | 0.800 | 0.900 | 0.814 |
| 060810. | *Silence of the Lambs* | | 1.042 | 1.135 | 1.106 | 1.011 | 0.997 | 1.055 | 1.020 | 1.065 | 1.022 | 1.083 | 1.121 |
| No.R.C. | *Terminator I* | 0.880 | 0.797 | 0.783 | 0.774 | 0.763 | 0.778 | 0.828 | 0.852 | 0.862 | 0.908 | 0.941 | 0.986 |
| | *Terminator I* | | 1.046 | 1.047 | 0.980 | 0.881 | 0.896 | 0.733 | 0.800 | 0.676 | 0.603 | 0.714 | 0.623 |
| | *Snowboard with Comm* | 0.852 | 0.739 | 0.697 | 0.666 | 0.621 | 0.612 | 0.619 | 0.589 | 0.600 | 0.519 | 0.506 | 0.444 |
| | *Snowboard with Comm* | | 1.130 | 1.063 | 0.872 | 0.907 | 0.851 | 0.692 | 0.672 | 0.641 | 0.705 | 0.608 | 0.614 |
| | *Oprah w/o Comm* | 0.845 | 0.863 | 0.835 | 0.818 | 0.804 | 0.822 | 0.838 | 0.786 | 0.789 | 0.871 | 0.751 | 0.798 |
| | *Oprah w/o Comm* | | 1.115 | 1.192 | 1.207 | 1.096 | 1.101 | 0.991 | 1.078 | 1.090 | 0.962 | 1.158 | 0.931 |
| | *ParkingLot* | 0.666 | 0.460 | 0.428 | 0.461 | 0.525 | 0.576 | 0.621 | 0.689 | 0.737 | 0.835 | 0.764 | 0.844 |
| | *ParkingLot* | | 0.955 | 0.745 | 0.596 | 0.405 | 0.529 | 0.453 | 0.443 | 0.459 | 0.635 | 0.623 | 0.592 |
| | *LectureHQ-Reisslein* | 0.693 | 0.831 | 0.816 | 0.795 | 0.788 | 0.778 | 0.777 | 0.795 | 0.789 | 0.819 | 0.834 | 0.847 |
| | *LectureHQ-Reisslein* | | 1.050 | 1.010 | 0.972 | 0.982 | 0.929 | 0.921 | 0.937 | 0.871 | 0.845 | 0.605 | 0.790 |
| CIF | *Silence of the Lambs* | 0.943 | 0.924 | 0.907 | 0.911 | 0.905 | 0.908 | 0.867 | 0.884 | 0.771 | 0.783 | 0.895 | 0.813 |
| 101010. | *Silence of the Lambs* | | 1.029 | 1.126 | 1.104 | 1.014 | 1.000 | 1.061 | 1.031 | 1.063 | 1.019 | 1.078 | 1.103 |
| No.R.C. | *Terminator I* | 0.891 | 0.796 | 0.780 | 0.770 | 0.761 | 0.774 | 0.822 | 0.842 | 0.853 | 0.901 | 0.937 | 0.975 |
| | *Terminator I* | | 1.037 | 1.039 | 0.970 | 0.871 | 0.876 | 0.717 | 0.734 | 0.668 | 0.567 | 0.678 | 0.604 |
| | *Snowboard with Comm* | 0.876 | 0.740 | 0.696 | 0.669 | 0.624 | 0.612 | 0.614 | 0.596 | 0.587 | 0.511 | 0.506 | 0.437 |
| | *Snowboard with Comm* | | 1.111 | 1.064 | 0.881 | 0.917 | 0.843 | 0.690 | 0.686 | 0.651 | 0.715 | 0.624 | 0.620 |
| | *Oprah w/o Comm* | 0.915 | 0.855 | 0.826 | 0.809 | 0.787 | 0.802 | 0.816 | 0.756 | 0.755 | 0.840 | 0.719 | 0.740 |
| | *Oprah w/o Comm* | | 1.089 | 1.168 | 1.188 | 1.072 | 1.077 | 0.960 | 1.036 | 1.090 | 0.907 | 1.112 | 0.892 |
| | *ParkingLot* | 0.655 | 0.411 | 0.367 | 0.384 | 0.429 | 0.475 | 0.500 | 0.565 | 0.639 | 0.727 | 0.650 | 0.747 |
| | *ParkingLot* | | 0.918 | 0.685 | 0.518 | 0.328 | 0.419 | 0.232 | 0.250 | 0.284 | 0.182 | 0.375 | 0.352 |
| | *LectureHQ-Reisslein* | 0.729 | 0.829 | 0.816 | 0.797 | 0.786 | 0.773 | 0.770 | 0.777 | 0.780 | 0.804 | 0.810 | 0.831 |
| | *LectureHQ-Reisslein* | | 1.048 | 1.003 | 0.963 | 0.968 | 0.908 | 0.909 | 0.927 | 0.875 | 0.856 | 0.770 | 0.803 |
| CIF | *Silence of the Lambs* | 0.899 | 0.922 | 0.906 | 0.906 | 0.906 | 0.894 | 0.844 | 0.872 | 0.753 | 0.760 | 0.878 | 0.807 |
| 101416. | *Silence of the Lambs* | | 1.003 | 1.100 | 1.086 | 1.013 | 1.001 | 1.005 | 0.979 | 0.983 | 0.996 | 1.064 | 1.064 |
| No.R.C. | *Terminator I* | 0.854 | 0.786 | 0.773 | 0.758 | 0.750 | 0.765 | 0.808 | 0.811 | 0.821 | 0.884 | 0.905 | 0.945 |
| | *Terminator I* | | 1.012 | 1.020 | 0.958 | 0.874 | 0.882 | 0.713 | 0.713 | 0.744 | 0.586 | 0.687 | 0.637 |
| | *Snowboard with Comm* | 0.840 | 0.758 | 0.712 | 0.688 | 0.650 | 0.644 | 0.609 | 0.624 | 0.590 | 0.520 | 0.552 | 0.467 |
| | *Snowboard with Comm* | | 1.088 | 1.051 | 0.926 | 0.942 | 0.858 | 0.684 | 0.704 | 0.627 | 0.701 | 0.655 | 0.572 |
| | *Oprah w/o Comm* | 0.807 | 0.861 | 0.852 | 0.824 | 0.799 | 0.815 | 0.820 | 0.782 | 0.767 | 0.822 | 0.740 | 0.777 |
| | *Oprah w/o Comm* | | 1.019 | 1.102 | 1.138 | 1.081 | 1.060 | 0.969 | 1.038 | 1.086 | 0.924 | 1.056 | 0.929 |
| | *ParkingLot* | 0.598 | 0.381 | 0.332 | 0.340 | 0.393 | 0.476 | 0.501 | 0.557 | 0.624 | 0.695 | 0.646 | 0.744 |
| | *ParkingLot* | | 0.914 | 0.669 | 0.505 | 0.252 | 0.389 | 0.187 | 0.270 | 0.249 | 0.137 | 0.222 | 0.326 |
| | *LectureHQ-Reisslein* | 0.644 | 0.812 | 0.796 | 0.773 | 0.765 | 0.744 | 0.727 | 0.731 | 0.768 | 0.787 | 0.816 | 0.811 |
| | *LectureHQ-Reisslein* | | 1.025 | 0.973 | 0.939 | 0.956 | 0.890 | 0.889 | 0.916 | 0.867 | 0.853 | 0.781 | 0.821 |
| CIF | *Silence of the Lambs* | 0.906 | 0.911 | 0.895 | 0.893 | 0.890 | 0.874 | 0.812 | 0.858 | 0.728 | 0.741 | 0.854 | 0.788 |
| 242424. | *Silence of the Lambs* | | 0.981 | 1.074 | 1.052 | 1.005 | 0.985 | 0.962 | 0.951 | 0.899 | 0.915 | 1.067 | 0.993 |
| No.R.C. | *Terminator I* | 0.855 | 0.773 | 0.763 | 0.749 | 0.739 | 0.734 | 0.784 | 0.767 | 0.795 | 0.857 | 0.863 | 0.932 |
| | *Terminator I* | | 0.991 | 0.995 | 0.966 | 0.886 | 0.894 | 0.747 | 0.703 | 0.754 | 0.617 | 0.672 | 0.687 |
| | *Snowboard with Comm* | 0.860 | 0.780 | 0.734 | 0.710 | 0.684 | 0.677 | 0.616 | 0.660 | 0.565 | 0.539 | 0.637 | 0.535 |
| | *Snowboard with Comm* | | 1.058 | 1.020 | 0.912 | 0.931 | 0.879 | 0.661 | 0.657 | 0.598 | 0.671 | 0.677 | 0.541 |
| | *Oprah w/o Comm* | 0.838 | 0.844 | 0.838 | 0.827 | 0.821 | 0.820 | 0.806 | 0.780 | 0.744 | 0.781 | 0.685 | 0.752 |

Table 3: *continued*

| Enc. M. | Video | Aggregation level $a$ [frames] 1 | 12 | 24 | 48 | 96 | 192 | 300 | 396 | 504 | 600 | 696 | 792 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Oprah w/o Comm* | | 0.949 | 1.029 | 1.081 | 1.044 | 1.073 | 0.977 | 1.008 | 1.034 | 0.928 | 0.946 | 0.973 |
| | *ParkingLot* | 0.593 | 0.341 | 0.285 | 0.283 | 0.328 | 0.425 | 0.520 | 0.527 | 0.603 | 0.694 | 0.671 | 0.727 |
| | *ParkingLot* | | 0.930 | 0.689 | 0.492 | 0.203 | 0.343 | 0.134 | 0.282 | 0.271 | 0.263 | 0.391 | 0.372 |
| | *LectureHQ-Reisslein* | 0.663 | 0.779 | 0.757 | 0.727 | 0.696 | 0.650 | 0.618 | 0.608 | 0.644 | 0.648 | 0.706 | 0.724 |
| | *LectureHQ-Reisslein* | | 1.001 | 0.952 | 0.909 | 0.889 | 0.830 | 0.789 | 0.781 | 0.835 | 0.767 | 0.741 | 0.664 |
| CIF | *Silence of the Lambs* | 0.899 | 0.908 | 0.894 | 0.891 | 0.873 | 0.856 | 0.813 | 0.856 | 0.738 | 0.738 | 0.821 | 0.782 |
| 303030. | *Silence of the Lambs* | | 0.975 | 1.071 | 1.035 | 0.993 | 0.965 | 0.982 | 0.896 | 0.872 | 0.932 | 1.032 | 0.958 |
| No.R.C. | *Terminator I* | 0.851 | 0.770 | 0.760 | 0.744 | 0.728 | 0.728 | 0.782 | 0.763 | 0.792 | 0.865 | 0.848 | 0.954 |
| | *Terminator I* | | 0.987 | 0.986 | 0.958 | 0.884 | 0.891 | 0.764 | 0.694 | 0.747 | 0.615 | 0.672 | 0.699 |
| | *Snowboard with Comm* | 0.858 | 0.787 | 0.741 | 0.719 | 0.693 | 0.685 | 0.619 | 0.663 | 0.572 | 0.560 | 0.668 | 0.581 |
| | *Snowboard with Comm* | | 1.047 | 1.008 | 0.907 | 0.911 | 0.859 | 0.639 | 0.646 | 0.604 | 0.668 | 0.693 | 0.531 |
| | *Oprah w/o Comm* | 0.823 | 0.814 | 0.812 | 0.804 | 0.809 | 0.798 | 0.799 | 0.801 | 0.721 | 0.782 | 0.704 | 0.743 |
| | *Oprah w/o Comm* | | 0.932 | 1.009 | 1.065 | 1.020 | 1.048 | 1.004 | 0.973 | 1.014 | 0.911 | 0.922 | 0.951 |
| | *ParkingLot* | 0.586 | 0.332 | 0.273 | 0.262 | 0.294 | 0.385 | 0.513 | 0.463 | 0.551 | 0.650 | 0.658 | 0.681 |
| | *ParkingLot* | | 0.944 | 0.706 | 0.502 | 0.197 | 0.343 | 0.124 | 0.347 | 0.256 | 0.239 | 0.395 | 0.344 |
| | *LectureHQ-Reisslein* | 0.659 | 0.783 | 0.759 | 0.735 | 0.700 | 0.644 | 0.638 | 0.606 | 0.660 | 0.684 | 0.761 | 0.754 |
| | *LectureHQ-Reisslein* | | 0.977 | 0.937 | 0.902 | 0.873 | 0.818 | 0.755 | 0.769 | 0.823 | 0.703 | 0.738 | 0.652 |
| CIF | *Silence of the Lambs* | 0.893 | 0.904 | 0.887 | 0.874 | 0.865 | 0.851 | 0.818 | 0.859 | 0.730 | 0.745 | 0.846 | 0.770 |
| 64kbps | *Silence of the Lambs* | | 0.973 | 1.062 | 1.039 | 1.007 | 0.984 | 0.981 | 0.894 | 0.876 | 0.876 | 1.034 | 0.960 |
| | *Terminator I* | 0.851 | 0.770 | 0.760 | 0.746 | 0.731 | 0.723 | 0.781 | 0.756 | 0.791 | 0.861 | 0.839 | 0.951 |
| | *Terminator I* | | 0.987 | 0.983 | 0.962 | 0.885 | 0.899 | 0.763 | 0.703 | 0.749 | 0.622 | 0.673 | 0.689 |
| | *Snowboard with Comm* | 0.862 | 0.789 | 0.744 | 0.720 | 0.698 | 0.695 | 0.622 | 0.669 | 0.591 | 0.573 | 0.686 | 0.599 |
| | *Snowboard with Comm* | | 1.044 | 1.006 | 0.895 | 0.907 | 0.869 | 0.637 | 0.640 | 0.606 | 0.671 | 0.686 | 0.558 |
| | *Oprah w/o Comm* | 0.825 | 0.817 | 0.811 | 0.800 | 0.806 | 0.792 | 0.797 | 0.801 | 0.728 | 0.784 | 0.701 | 0.748 |
| | *Oprah w/o Comm* | | 0.929 | 1.002 | 1.059 | 1.009 | 1.041 | 0.999 | 0.953 | 1.001 | 0.909 | 0.912 | 0.940 |
| | *ParkingLot* | 0.585 | 0.331 | 0.271 | 0.259 | 0.287 | 0.376 | 0.506 | 0.449 | 0.538 | 0.637 | 0.643 | 0.677 |
| | *ParkingLot* | | 0.947 | 0.709 | 0.506 | 0.200 | 0.352 | 0.119 | 0.353 | 0.245 | 0.218 | 0.380 | 0.331 |
| | *LectureHQ-Reisslein* | 0.656 | 0.783 | 0.759 | 0.733 | 0.703 | 0.641 | 0.645 | 0.603 | 0.669 | 0.700 | 0.759 | 0.742 |
| | *LectureHQ-Reisslein* | | 0.969 | 0.936 | 0.900 | 0.884 | 0.820 | 0.760 | 0.764 | 0.831 | 0.717 | 0.744 | 0.644 |
| CIF | *Silence of the Lambs* | 0.896 | 0.904 | 0.888 | 0.874 | 0.866 | 0.851 | 0.817 | 0.860 | 0.730 | 0.746 | 0.847 | 0.770 |
| 128kbps | *Silence of the Lambs* | | 0.973 | 1.062 | 1.039 | 1.007 | 0.982 | 0.983 | 0.894 | 0.876 | 0.877 | 1.037 | 0.959 |
| R.C. | *Terminator I* | 0.851 | 0.767 | 0.761 | 0.746 | 0.731 | 0.723 | 0.781 | 0.756 | 0.791 | 0.861 | 0.839 | 0.951 |
| | *Terminator I* | | 0.987 | 0.982 | 0.966 | 0.890 | 0.903 | 0.765 | 0.703 | 0.751 | 0.625 | 0.676 | 0.691 |
| | *Snowboard with Comm* | 0.863 | 0.789 | 0.744 | 0.720 | 0.698 | 0.695 | 0.622 | 0.669 | 0.591 | 0.573 | 0.686 | 0.598 |
| | *Snowboard with Comm* | | 1.044 | 1.006 | 0.895 | 0.907 | 0.868 | 0.637 | 0.640 | 0.606 | 0.671 | 0.687 | 0.558 |
| | *Oprah without Comm* | 0.826 | 0.817 | 0.811 | 0.800 | 0.806 | 0.792 | 0.797 | 0.801 | 0.728 | 0.784 | 0.700 | 0.747 |
| | *Oprah without Comm* | | 0.929 | 1.001 | 1.058 | 1.009 | 1.041 | 0.999 | 0.952 | 1.002 | 0.909 | 0.911 | 0.940 |
| | *ParkingLot* | 0.585 | 0.331 | 0.271 | 0.259 | 0.287 | 0.376 | 0.506 | 0.449 | 0.538 | 0.636 | 0.643 | 0.677 |
| | *ParkingLot* | 0.947 | | 0.710 | 0.506 | 0.199 | 0.354 | 0.120 | 0.353 | 0.246 | 0.215 | 0.380 | 0.335 |
| | *LectureHQ-Reisslein* | 0.657 | 0.783 | 0.758 | 0.733 | 0.702 | 0.640 | 0.644 | 0.603 | 0.668 | 0.700 | 0.759 | 0.742 |
| | *LectureHQ-Reisslein* | | 0.969 | 0.935 | 0.899 | 0.883 | 0.821 | 0.760 | 0.765 | 0.831 | 0.716 | 0.743 | 0.644 |
| CIF | *Silence of the Lambs* | 0.784 | 0.822 | 0.812 | 0.801 | 0.778 | 0.744 | 0.729 | 0.736 | 0.678 | 0.694 | 0.777 | 0.765 |
| R.C. | *Silence of the Lambs* | | 0.902 | 0.945 | 0.923 | 0.913 | 0.889 | 0.952 | 0.815 | 0.824 | 0.791 | 0.809 | 0.906 |
| 256kbps | *Terminator I* | 0.851 | 0.777 | 0.764 | 0.745 | 0.729 | 0.722 | 0.781 | 0.754 | 0.788 | 0.860 | 0.837 | 0.948 |
| | *Terminator I* | | 0.990 | 0.988 | 0.976 | 0.898 | 0.900 | 0.788 | 0.709 | 0.782 | 0.687 | 0.693 | 0.736 |
| | *Snowboard with Comm* | 0.858 | 0.786 | 0.742 | 0.720 | 0.700 | 0.697 | 0.621 | 0.674 | 0.585 | 0.567 | 0.690 | 0.585 |
| | *Snowboard with Comm* | | 1.034 | 1.003 | 0.890 | 0.886 | 0.846 | 0.633 | 0.640 | 0.662 | 0.675 | 0.726 | 0.573 |
| | *Oprah w/o Comm* | 0.790 | 0.808 | 0.795 | 0.799 | 0.780 | 0.740 | 0.723 | 0.743 | 0.650 | 0.660 | 0.621 | 0.688 |
| | *Oprah w/o Comm* | | 0.885 | 0.944 | 0.987 | 0.949 | 0.929 | 0.923 | 0.819 | 0.908 | 0.777 | 0.782 | 0.771 |
| | *ParkingLot* | 0.586 | 0.331 | 0.270 | 0.260 | 0.285 | 0.371 | 0.505 | 0.460 | 0.530 | 0.631 | 0.637 | 0.672 |
| | *ParkingLot* | | 0.948 | 0.693 | 0.509 | 0.201 | 0.354 | 0.146 | 0.348 | 0.231 | 0.178 | 0.394 | 0.362 |
| | *LectureHQ-Reisslein* | 0.251 | 0.511 | 0.506 | 0.489 | 0.460 | 0.455 | 0.466 | 0.437 | 0.419 | 0.523 | 0.425 | 0.562 |
| | *LectureHQ-Reisslein* | | 0.591 | 0.537 | 0.488 | 0.273 | -0.018 | -0.139 | -0.194 | -0.175 | -0.150 | -0.227 | -0.028 |
| CIF | *ParkingLot* | 0.423 | 0.264 | 0.220 | 0.218 | 0.203 | 0.209 | 0.256 | 0.221 | 0.249 | 0.328 | 0.254 | 0.276 |
| R.C. | *ParkingLot* | | 0.609 | 0.430 | 0.299 | 0.129 | -0.008 | -0.077 | -0.150 | -0.318 | -0.085 | -0.219 | 0.002 |
| 512kbps | *LectureHQ-Reisslein* | 0.127 | 0.363 | 0.377 | 0.325 | 0.374 | 0.307 | 0.376 | 0.375 | 0.274 | 0.422 | 0.448 | 0.316 |
| | *LectureHQ-Reisslein* | | 0.085 | -0.009 | 0.058 | 0.074 | 0.198 | -0.034 | 0.115 | 0.024 | -0.168 | 0.070 | 0.331 |
| CIF | *ParkingLot* | 0.212 | 0.324 | 0.312 | 0.326 | 0.337 | 0.325 | 0.418 | 0.285 | 0.392 | 0.459 | 0.268 | 0.220 |
| R.C. | *ParkingLot* | | 0.716 | 0.470 | 0.014 | -0.113 | -0.098 | -0.206 | -0.094 | -0.092 | -0.183 | -0.024 | 0.020 |
| 1024kbps | *LectureHQ-Reisslein* | 0.124 | 0.254 | 0.265 | 0.308 | 0.309 | 0.338 | 0.312 | 0.264 | 0.364 | 0.331 | 0.050 | 0.197 |
| | *LectureHQ-Reisslein* | | 0.021 | -0.014 | -0.000 | 0.086 | -0.003 | 0.160 | 0.113 | 0.168 | 0.119 | 0.332 | 0.104 |

Table 4 gives the Hurst parameter estimated using the variance time plot for the frame size trace, as well as the scaling parameters $\underline{c}_f$ and $\alpha$ (also expressed as $H = (1+\alpha)/2$) estimated from the logscale diagram. Figures 7, 8, and 9 give the variance-time plots, the pox plots of R/S (for $a = 12$), and the periodogram (for $a = 12$). As has been widely studied (see for instance [1]) the $H$ estimates for a given video trace typically decrease as the aggregation level increases from $a = 1$ to roughly $a = 192$ and then are more or less stable for larger $a$. Therefore, we focus primarily on the $H$ estimates for aggregation levels of a few hundred frames in our discussion. We observe from our analysis of the different quality levels (without rate

control) for a given video, that there appears to be no clear trend in the $H$ value estimates for the different quality levels. For some videos the $H$ estimates decrease as the quality decreases (e.g., *Oprah without Commercials*), whereas for other videos the $H$ estimates slightly increase as the quality decreases (e.g., *Lecture–Reisslein*). For most videos the $H$ estimates are roughly the same when comparing different quality levels.

The behavior of these long range dependence properties as a function of the quality level is in stark contrast to the behavior of the variability ($CoV_X$ and $X_{\max}/\bar{X}$) observed above. The implications of these findings will be studied in detail in future work. Our large scale study re-confirms that the variance-time analysis tends to give smaller $H$ estimates than the other methods, which is formally analyzed in [2]. Also, as expected (see for instance [3]), the encodings with rate control appear not to have long range dependence properties. The 64 kbps encodings are an exception. They tend to have some degree of long range dependence, which appears to be due to the inability of the employed encoder to meet this small target bit rate.

Some logscale diagrams are given in Figure 10. We observe that the logscale diagrams give, in many cases, $H$ estimates very close to one or above one, which should be viewed with caution. The $H$ estimates around and above one appear to be due to the fact that the employed logscale estimation assumes Gaussian time series, whereas our trace data is typically non-Gaussian.

The logscale diagrams in Figure 10 typically exhibit a "knee" around scale $j = 4$ or $j = 5$. This time scale, which corresponds to roughly 16 to 32 frames (i.e., about half a second to one second of video) may be a transition point from short-term to long-term scaling. This issue and its implications are to be studied in detail in future work. For the longer scales, the logscale plots indicate a reasonable level of scaling, with some "bumps" for very large scales. The very small $H$ estimate of 0.659 for the low quality *Silence of the Lambs* encoding is due to the employed automated estimation procedure, which chose the range from $j = 10$ to $j = 14$, as illustrated in Figure 10c. An estimation over the range from $j = 5$ to $j = 10$ would have given an $H$ estimate of 1.158.

Next, we examine the normalized form $\underline{c}_f = c_f/S_X^2$ of the second parameter of long range dependence. For the videos without rate control there appear to be two trends:

1. The videos with relatively large $\underline{c}_f$ estimates tend to have relatively small H estimates from the logscale diagram.

2. The $\underline{c}_f$ tends to decrease as the quality level decreases.

Again, we note that these trends need to be viewed with caution, since many of the H estimates from the logscale diagrams are about one or larger than one, calling the validity of

the entire estimation procedure of both H and $\underline{c}_f$ in question. In general [4], the first parameter of long range dependence $\alpha$ (or H) indicates the characteristic of the scaling behavior (including the presence or absence of long range dependence). The second parameter $\underline{c}_f$, on the other hand, indicates the size of the effects of long range dependence. Typically, a larger $\underline{c}_f$ indicates more mass in the tail of the queue length distributions and thus larger queuing delays. The two observations noted above call for a more detailed study of these phenomena in context of video traffic. We note here briefly that observation (2) appears to contradict the earlier observations that the lower quality video is more bursty.

Table 4: Hurst parameters estimated from variance time plot, scaling parameters estimated from logscale diagram .

| | | VT | Logscale Diagram | | |
|---|---|---|---|---|---|
| Enc. M. | Video | $H$ | $\underline{c}_f$ | $\alpha$ | $H$ |
| QCIF | *Citizen Kane* | 0.859 | 0.068 | 0.850 | 0.925 |
| H.Q. | *Die Hard I* | 0.701 | 0.317 | 0.603 | 0.802 |
| No R.C. | *Jurassic Park I* | 0.663 | 0.019 | 1.101 | 1.051 |
| | *Silence of the Lambs* | 0.909 | 0.024 | 1.004 | 1.002 |
| | *Star Wars IV* | 0.824 | 0.248 | 0.601 | 0.800 |
| | *Star Wars V* | 0.736 | 0.038 | 0.976 | 0.988 |
| | *The Firm* | 0.812 | 0.011 | 1.159 | 1.079 |
| | *Terminator I* | 0.829 | 0.050 | 0.917 | 0.958 |
| | *Total Recall* | 0.747 | 0.028 | 0.984 | 0.992 |
| | *Aladdin* | 0.877 | 0.023 | 1.076 | 1.038 |
| | *Cinderella* | 0.907 | 0.125 | 0.751 | 0.875 |
| | *Baseball with Comm* | 0.790 | 0.507 | 0.603 | 0.801 |
| | *Snowboard with Comm* | 0.751 | 9.485 | 0.168 | 0.584 |
| | *Oprah w/o Comm* | 0.952 | 0.036 | 0.901 | 0.950 |
| | *Tonight Show w/o Comm* | 0.963 | 0.070 | 0.735 | 0.868 |
| | *Lecture-Gupta* | 0.863 | 0.005 | 1.063 | 1.031 |
| | *Lecture-Reisslein* | 0.954 | 0.001 | 1.323 | 1.161 |
| QCIF | *Jurassic Park I* | 0.611 | 0.002 | 1.328 | 1.164 |
| H.–M.Q. | *Star Wars IV* | 0.788 | 0.017 | 0.943 | 0.971 |
| No R.C. | *The Firm* | 0.833 | 0.002 | 1.397 | 1.198 |
| | *Tonight Show w/o Comm* | 0.934 | 0.111 | 0.612 | 0.806 |
| QCIF | *Citizen Kane* | 0.866 | 0.029 | 0.761 | 0.880 |
| M.Q. | *Die Hard I* | 0.708 | 0.004 | 1.128 | 1.064 |
| No R.C. | *Jurassic Park I* | 0.604 | 0.003 | 1.151 | 1.076 |
| | *Silence of the Lambs* | 0.895 | 0.004 | 1.129 | 1.064 |
| | *Star Wars IV* | 0.804 | 0.010 | 0.923 | 0.961 |
| | *Star Wars V* | 0.768 | 0.014 | 0.930 | 0.965 |
| | *The Firm* | 0.838 | 0.006 | 1.048 | 1.024 |
| | *Terminator I* | 0.828 | 0.020 | 0.887 | 0.943 |
| | *Total Recall* | 0.723 | 0.004 | 1.107 | 1.054 |
| | *Aladdin* | 0.877 | 0.018 | 0.921 | 0.961 |
| | *Cinderella* | 0.792 | 0.076 | 0.694 | 0.847 |
| | *Baseball with Comm* | 0.685 | 0.008 | 1.055 | 1.028 |
| | *Snowboard with Comm* | 0.638 | 1.944 | 0.181 | 0.591 |
| | *Oprah w/o Comm* | 0.871 | 0.008 | 0.910 | 0.955 |
| | *Tonight Show w/o Comm* | 0.942 | 0.058 | 0.611 | 0.805 |
| | *Lecture-Gupta* | 0.777 | 0.000 | 1.248 | 1.124 |
| | *Lecture-Reisslein* | 0.938 | 0.000 | 1.341 | 1.171 |
| QCIF | *Jurassic Park I* | 0.616 | 0.010 | 1.141 | 1.070 |
| M.–L.Q. | *Star Wars IV* | 0.814 | 0.392 | 0.464 | 0.732 |
| No R.C. | *The Firm* | 0.830 | 0.028 | 0.923 | 0.961 |
| | *Tonight Show w/o Comm* | 0.943 | 1.025 | 0.628 | 0.814 |
| QCIF | *Citizen Kane* | 0.844 | 0.006 | 1.115 | 1.058 |
| L.Q. | *Die Hard I* | 0.722 | 0.047 | 0.841 | 0.920 |

Table 4: *continued*

| Enc. M. | Video | VT $H$ | Logscale Diagram $\underline{c}_f$ | $\alpha$ | $H$ |
|---|---|---|---|---|---|
| No R.C. | *Jurassic Park I* | 0.628 | 0.003 | 1.281 | 1.141 |
| | *Silence of the Lambs* | 0.866 | 1.092 | 0.318 | 0.659 |
| | *Star Wars IV* | 0.773 | 0.019 | 0.940 | 0.970 |
| | *Star Wars V* | 0.756 | 0.048 | 0.811 | 0.905 |
| | *The Firm* | 0.821 | 0.057 | 0.743 | 0.871 |
| | *Terminator I* | 0.845 | 0.029 | 0.900 | 0.950 |
| | *Total Recall* | 0.706 | 0.010 | 1.082 | 1.041 |
| | *Aladdin* | 0.859 | 0.046 | 0.836 | 0.918 |
| | *Cinderella* | 0.775 | 0.081 | 0.759 | 0.880 |
| | *Baseball with Comm* | 0.586 | 0.274 | 0.569 | 0.784 |
| | *Snowboard with Comm* | 0.580 | 1.587 | 0.223 | 0.612 |
| | *Oprah w/o Comm* | 0.780 | 0.007 | 1.056 | 1.028 |
| | *Tonight Show w/o Comm* | 0.936 | 0.000 | 1.793 | 1.397 |
| | *Lecture-Gupta* | 0.729 | 0.002 | 0.932 | 0.966 |
| | *Lecture-Reisslein* | 0.948 | 0.002 | 1.108 | 1.054 |
| QCIF | *Citizen Kane* | 0.666 | 1.185 | 0.081 | 0.541 |
| R.C. | *Die Hard I* | 0.719 | 0.048 | 0.836 | 0.918 |
| 64 kbps | *Jurassic Park I* | 0.625 | 0.016 | 0.982 | 0.991 |
| | *Silence of the Lambs* | 0.763 | 23827.756 | -1.170 | -0.085 |
| | *Star Wars IV* | 0.735 | 11.513 | -0.218 | 0.391 |
| | *Star Wars V* | 0.728 | 0.153 | 0.585 | 0.792 |
| | *The Firm* | 0.714 | 0.017 | 0.857 | 0.929 |
| | *Terminator I* | 0.837 | 0.031 | 0.874 | 0.937 |
| | *Total Recall* | 0.680 | 0.011 | 0.992 | 0.996 |
| | *Aladdin* | 0.857 | 0.046 | 0.835 | 0.917 |
| | *Cinderella* | 0.763 | 0.082 | 0.753 | 0.876 |
| | *Baseball with Comm* | 0.575 | 0.302 | 0.547 | 0.774 |
| | *Snowboard with Comm* | 0.583 | 1.355 | 0.243 | 0.621 |
| | *Oprah w/o Comm* | 0.775 | 0.013 | 0.917 | 0.959 |
| | *Tonight Show w/o Comm* | 0.773 | 0.000 | 1.182 | 1.091 |
| | *Lecture-Gupta* | 0.724 | 0.003 | 0.918 | 0.959 |
| | *Lecture-Reisslein* | 0.932 | 0.002 | 1.106 | 1.053 |
| QCIF | *Citizen Kane* | -0.282 | 25406.062 | -2.233 | -0.616 |
| R.C. | *Die Hard I* | -0.293 | 16539.776 | -1.872 | -0.436 |
| 128 kbps | *Jurassic Park I* | -0.540 | 2521.243 | -1.169 | -0.084 |
| | *Silence of the Lambs* | -0.748 | 0.359 | -1.249 | -0.124 |
| | *Star Wars IV* | -0.049 | 24.640 | -1.694 | -0.347 |
| | *Star Wars V* | -0.124 | 511.025 | -1.884 | -0.442 |
| | *The Firm* | -0.678 | 2140557.017 | -2.966 | -0.983 |
| | *Terminator I* | -0.078 | 111350.456 | -1.829 | -0.415 |
| | *Total Recall* | -0.071 | 650.269 | -1.709 | -0.355 |
| | *Aladdin* | 0.476 | 1655151012.080 | -2.662 | -0.831 |
| | *Cinderella* | -0.522 | 1677.828 | -1.267 | -0.134 |
| | *Baseball with Comm* | 0.300 | 38736466387941.400 | -4.603 | -1.802 |
| | *Snowboard with Comm* | 0.088 | 65.610 | -0.685 | 0.157 |
| | *Oprah w/o Comm* | 0.062 | 13008691.086 | -3.022 | -1.011 |
| | *Tonight Show w/o Comm* | -0.227 | 7328.228 | -1.825 | -0.413 |
| | *Lecture-Gupta* | -1.154 | 8.860 | -1.513 | -0.257 |
| | *Lecture-Reisslein* | -0.695 | 1192.844 | -1.525 | -0.263 |
| QCIF | *Citizen Kane* | 0.054 | 2.514 | -1.288 | -0.144 |
| R.C. | *Die Hard I* | 0.020 | 0.624 | -1.081 | -0.041 |
| 256 kbps | *Jurassic Park I* | 0.075 | 1.815 | -1.254 | -0.127 |
| | *Silence of the Lambs* | -0.190 | 389.806 | -1.917 | -0.458 |
| | *Star Wars IV* | 0.076 | 2.776 | -1.314 | -0.157 |
| | *Star Wars V* | -0.027 | 3.727 | -1.365 | -0.183 |
| | *The Firm* | 0.046 | 2.823 | -1.299 | -0.150 |
| | *Terminator I* | 0.165 | 4.609 | -1.304 | -0.152 |
| | *Total Recall* | 0.032 | 3.094 | -1.301 | -0.151 |
| | *Aladdin* | 0.053 | 78.487 | -1.767 | -0.384 |
| | *Cinderella* | -0.284 | 5.941 | -1.392 | -0.196 |

Table 4: *continued*

| Enc. M. | Video | VT $H$ | Logscale Diagram $\underline{c}_f$ | $\alpha$ | $H$ |
|---|---|---|---|---|---|
| | *Baseball with Comm* | -0.012 | 6.620 | -1.432 | -0.216 |
| | *Snowboard with Comm* | -0.051 | 20.291 | -1.485 | -0.243 |
| | *Oprah w/o Comm* | 0.104 | 1.364 | -1.266 | -0.133 |
| | *Tonight Show w/o Comm* | 0.186 | 11.832 | -1.580 | -0.290 |
| | *Lecture-Gupta* | 0.126 | 0.032 | -1.017 | -0.008 |
| | *Lecture-Reisslein* | 0.042 | 0.058 | -0.924 | 0.038 |
| CIF H.Q. No.R.C. | *Silence of the Lambs* | 0.908 | 0.000 | 2.205 | 1.603 |
| CIF M.Q. No.R.C. | *Silence of the Lambs* | 0.869 | 0.000 | 1.869 | 1.434 |
| CIF L.Q. No R.C. | *Silence of the Lambs* | 0.838 | 0.030 | 0.966 | 0.983 |
| CIF R.C. 64 kbps | *Silence of the Lambs* | 0.841 | 0.033 | 0.955 | 0.977 |
| CIF R.C. 128 kbps | *Silence of the Lambs* | 0.841 | 0.033 | 0.955 | 0.977 |
| CIF R.C. 256 kbps | *Silence of the Lambs* | 0.806 | 0.021 | 0.937 | 0.968 |

Table 5 gives the multiscaling parameter $\alpha_q$ for the orders $q = 0.5$, 1, 1.5, 2, 2.5, 3, 3.5, and 4. We observe in Table 5 that the scaling parameters tend to increase with increasing $q$. (Again with the exception of the low quality *Silence of the Lambs* encoding.) Note that the Hurst parameter estimate is given by $H = \alpha_2/2$ for the employed estimation with $c$ norm of one. We observe again that a number of estimates are around one or exceed one. The number of these "suspicious" $H$ estimates, however, is smaller than with the logscale plot estimation. This may be due to the fact that the multiscale estimation does not assume a Gaussian time series.

Table 5: Scaling parameters estimated from multiscale diagram.

| Enc. M. | Video | Multiscale Diagram, $\alpha_q$ for $q = 0.5$ | $q = 1$ | $q = 1.5$ | $q = 2$ | $q = 2.5$ | $q = 3$ | $q = 3.5$ | $q = 4$ |
|---|---|---|---|---|---|---|---|---|---|
| QCIF | *Citizen Kane* | 0.524 | 0.999 | 1.421 | 1.801 | 2.147 | 2.469 | 2.772 | 3.060 |
| H.Q. | *Die Hard I* | 0.415 | 0.818 | 1.208 | 1.582 | 1.940 | 2.282 | 2.608 | 2.921 |
| No.R.C. | *Jurassic Park I* | 0.547 | 1.070 | 1.581 | 2.095 | 2.614 | 3.131 | 3.639 | 4.139 |
| | *Silence of the Lambs* | 0.535 | 1.033 | 1.518 | 1.998 | 2.473 | 2.945 | 3.414 | 3.879 |
| | *Star Wars IV* | 0.425 | 0.825 | 1.207 | 1.574 | 1.929 | 2.274 | 2.611 | 2.942 |
| | *Star Wars V* | 0.503 | 1.001 | 1.487 | 1.961 | 2.424 | 2.877 | 3.322 | 3.758 |
| | *The Firm* | 0.549 | 1.097 | 1.636 | 2.160 | 2.666 | 3.154 | 3.627 | 4.092 |
| | *Terminator I* | 0.510 | 0.991 | 1.455 | 1.905 | 2.344 | 2.775 | 3.199 | 3.618 |
| | *Total Recall* | 0.521 | 1.016 | 1.489 | 1.942 | 2.377 | 2.794 | 3.196 | 3.583 |
| | *Aladdin* | 0.535 | 1.061 | 1.574 | 2.073 | 2.558 | 3.028 | 3.486 | 3.926 |
| | *Cinderella* | 0.485 | 0.938 | 1.360 | 1.752 | 2.115 | 2.453 | 2.772 | 3.080 |
| | *Baseball with Comm* | 0.406 | 0.798 | 1.178 | 1.545 | 1.906 | 2.261 | 2.616 | 2.970 |
| | *Snowboard with Comm* | 0.250 | 0.538 | 0.840 | 1.142 | 1.439 | 1.728 | 2.008 | 2.280 |
| | *Oprah w/o Comm* | 0.473 | 0.935 | 1.394 | 1.858 | 2.322 | 2.783 | 3.235 | 3.675 |

Table 5: *continued*

| Enc. M. | Video | Multiscale Diagram, $\alpha_q$ for $q=0.5$ | $q=1$ | $q=1.5$ | $q=2$ | $q=2.5$ | $q=3$ | $q=3.5$ | $q=4$ |
|---|---|---|---|---|---|---|---|---|---|
| | *Tonight Show w/o Comm* | 0.551 | 1.063 | 1.554 | 2.020 | 2.463 | 2.887 | 3.296 | 3.695 |
| | *Lecture-Gupta* | 0.673 | 1.187 | 1.609 | 1.987 | 2.343 | 2.687 | 3.025 | 3.361 |
| | *Lecture-Reisslein* | 0.692 | 1.310 | 1.840 | 2.294 | 2.700 | 3.079 | 3.446 | 3.807 |
| QCIF | *Jurassic Park I* | 0.581 | 1.158 | 1.736 | 2.316 | 2.891 | 3.453 | 3.998 | 4.538 |
| H.–M.Q. | *Star Wars IV* | 0.503 | 1.002 | 1.488 | 1.952 | 2.390 | 2.800 | 3.149 | 3.523 |
| No.R.C. | *The Firm* | 0.590 | 1.188 | 1.791 | 2.397 | 3.000 | 3.596 | 4.182 | 4.760 |
| | *Tonight Show w/o Comm* | 0.542 | 1.045 | 1.506 | 1.933 | 2.329 | 2.702 | 3.059 | 3.404 |
| QCIF | *Citizen Kane* | 0.515 | 0.968 | 1.367 | 1.717 | 2.027 | 2.304 | 2.556 | 2.789 |
| M.Q. | *Die Hard I* | 0.518 | 1.037 | 1.557 | 2.080 | 2.611 | 3.132 | 3.648 | 4.159 |
| No.R.C. | *Jurassic Park I* | 0.544 | 1.068 | 1.597 | 2.140 | 2.685 | 3.218 | 3.732 | 4.231 |
| | *Silence of the Lambs* | 0.548 | 1.092 | 1.621 | 2.136 | 2.622 | 3.085 | 3.536 | 3.980 |
| | *Star Wars IV* | 0.503 | 1.006 | 1.501 | 1.977 | 2.424 | 2.798 | 3.176 | 3.540 |
| | *Star Wars V* | 0.519 | 1.007 | 1.470 | 1.916 | 2.347 | 2.767 | 3.177 | 3.580 |
| | *The Firm* | 0.532 | 1.061 | 1.573 | 2.061 | 2.523 | 2.961 | 3.381 | 3.788 |
| | *Terminator I* | 0.516 | 1.001 | 1.460 | 1.896 | 2.314 | 2.718 | 3.112 | 3.498 |
| | *Total Recall* | 0.548 | 1.082 | 1.599 | 2.096 | 2.577 | 3.044 | 3.494 | 3.936 |
| | *Aladdin* | 0.500 | 0.989 | 1.461 | 1.917 | 2.357 | 2.783 | 3.195 | 3.598 |
| | *Cinderella* | 0.483 | 0.938 | 1.353 | 1.719 | 2.041 | 2.329 | 2.599 | 2.859 |
| | *Baseball with Comm* | 0.547 | 1.074 | 1.578 | 2.053 | 2.505 | 2.946 | 3.377 | 3.794 |
| | *Snowboard with Comm* | 0.292 | 0.593 | 0.888 | 1.167 | 1.427 | 1.667 | 1.890 | 2.100 |
| | *Oprah w/o Comm* | 0.511 | 0.986 | 1.437 | 1.874 | 2.299 | 2.714 | 3.118 | 3.512 |
| | *Tonight Show w/o Comm* | 0.545 | 1.042 | 1.500 | 1.920 | 2.307 | 2.669 | 3.015 | 3.349 |
| | *Lecture-Gupta* | 0.526 | 1.131 | 1.749 | 2.343 | 2.901 | 3.430 | 3.938 | 4.433 |
| | *Lecture-Reisslein* | 0.625 | 1.263 | 1.895 | 2.516 | 3.123 | 3.726 | 4.370 | 4.970 |
| QCIF | *Jurassic Park I* | 0.555 | 1.081 | 1.600 | 2.128 | 2.659 | 3.188 | 3.696 | 4.189 |
| M.–L.Q. | *Star Wars IV* | 0.395 | 0.761 | 1.104 | 1.430 | 1.741 | 2.040 | 2.329 | 2.609 |
| No R.C. | *The Firm* | 0.506 | 0.991 | 1.462 | 1.919 | 2.357 | 2.775 | 3.174 | 3.557 |
| | *Tonight Show w/o Comm* | 0.538 | 1.043 | 1.516 | 1.954 | 2.360 | 2.742 | 3.108 | 3.462 |
| QCIF | *Citizen Kane* | 0.535 | 1.075 | 1.611 | 2.135 | 2.645 | 3.140 | 3.625 | 4.104 |
| L.Q. | *Die Hard I* | 0.477 | 0.933 | 1.378 | 1.819 | 2.263 | 2.712 | 3.165 | 3.620 |
| No.R.C. | *Jurassic Park I* | 0.570 | 1.133 | 1.691 | 2.245 | 2.797 | 3.341 | 3.875 | 4.391 |
| | *Silence of the Lambs* | 0.455 | 0.826 | 1.094 | 1.243 | 1.290 | 1.270 | 1.214 | 1.143 |
| | *Star Wars IV* | 0.500 | 0.995 | 1.476 | 1.940 | 2.383 | 2.801 | 3.166 | 3.552 |
| | *Star Wars V* | 0.462 | 0.913 | 1.350 | 1.775 | 2.191 | 2.600 | 3.003 | 3.401 |
| | *The Firm* | 0.469 | 0.913 | 1.335 | 1.737 | 2.120 | 2.488 | 2.842 | 3.188 |
| | *Terminator I* | 0.507 | 0.989 | 1.452 | 1.899 | 2.332 | 2.751 | 3.158 | 3.554 |
| | *Total Recall* | 0.536 | 1.061 | 1.574 | 2.071 | 2.550 | 3.015 | 3.457 | 3.888 |
| | *Aladdin* | 0.477 | 0.945 | 1.400 | 1.844 | 2.275 | 2.695 | 3.105 | 3.508 |
| | *Cinderella* | 0.473 | 0.935 | 1.389 | 1.833 | 2.266 | 2.687 | 3.095 | 3.495 |
| | *Baseball with Comm* | 0.380 | 0.762 | 1.147 | 1.533 | 1.917 | 2.294 | 2.663 | 3.019 |
| | *Snowboard with Comm* | 0.308 | 0.614 | 0.917 | 1.213 | 1.495 | 1.760 | 2.006 | 2.235 |
| | *Oprah w/o Comm* | 0.494 | 1.011 | 1.542 | 2.081 | 2.618 | 3.144 | 3.660 | 4.155 |
| | *Tonight Show w/o Comm* | 0.789 | 1.527 | 2.250 | 2.923 | 3.535 | 4.094 | 4.612 | 5.103 |
| | *Lecture-Gupta* | 0.474 | 1.005 | 1.541 | 2.060 | 2.553 | 3.023 | 3.475 | 3.914 |
| | *Lecture-Reisslein* | 0.568 | 1.138 | 1.700 | 2.257 | 2.803 | 3.386 | 3.942 | 4.494 |
| QCIF | *Citizen Kane* | 0.365 | 0.615 | 0.851 | 1.078 | 1.292 | 1.496 | 1.692 | 1.883 |
| R.C. | *Die Hard I* | 0.484 | 0.939 | 1.378 | 1.813 | 2.252 | 2.696 | 3.145 | 3.597 |
| 64 kbps | *Jurassic Park I* | 0.488 | 0.965 | 1.456 | 1.965 | 2.479 | 2.984 | 3.474 | 3.948 |
| | *Silence of the Lambs* | 0.083 | -0.067 | -0.266 | -0.466 | -0.662 | -0.853 | -1.041 | -1.227 |
| | *Star Wars IV* | 0.194 | 0.388 | 0.606 | 0.826 | 1.036 | 1.231 | 1.411 | 1.577 |
| | *Star Wars V* | 0.414 | 0.817 | 1.183 | 1.508 | 1.791 | 2.062 | 2.321 | 2.560 |
| | *The Firm* | 0.472 | 0.959 | 1.422 | 1.840 | 2.221 | 2.583 | 2.931 | 3.288 |
| | *Terminator I* | 0.503 | 0.982 | 1.440 | 1.882 | 2.310 | 2.723 | 3.123 | 3.512 |
| | *Total Recall* | 0.495 | 0.990 | 1.476 | 1.951 | 2.406 | 2.839 | 3.248 | 3.637 |
| | *Aladdin* | 0.483 | 0.953 | 1.405 | 1.836 | 2.243 | 2.628 | 2.996 | 3.350 |
| | *Cinderella* | 0.467 | 0.929 | 1.386 | 1.834 | 2.271 | 2.696 | 3.108 | 3.510 |
| | *Baseball with Comm* | 0.381 | 0.755 | 1.133 | 1.512 | 1.890 | 2.262 | 2.623 | 2.973 |
| | *Snowboard with Comm* | 0.313 | 0.620 | 0.923 | 1.219 | 1.502 | 1.767 | 2.013 | 2.243 |
| | *Oprah w/o Comm* | 0.503 | 0.992 | 1.457 | 1.905 | 2.339 | 2.762 | 3.179 | 3.591 |
| | *Tonight Show w/o Comm* | 0.844 | 1.531 | 2.110 | 2.588 | 2.998 | 3.367 | 3.715 | 4.048 |

Table 5: *continued*

| Enc. M. | Video | Multiscale Diagram, $\alpha_q$ for $q=0.5$ | $q=1$ | $q=1.5$ | $q=2$ | $q=2.5$ | $q=3$ | $q=3.5$ | $q=4$ |
|---|---|---|---|---|---|---|---|---|---|
| | *Lecture-Gupta* | 0.482 | 1.001 | 1.507 | 1.978 | 2.411 | 2.817 | 3.206 | 3.584 |
| | *Lecture-Reisslein* | 0.557 | 1.126 | 1.704 | 2.289 | 2.880 | 3.473 | 4.003 | 4.569 |
| QCIF | *Citizen Kane* | -0.040 | -0.256 | -0.621 | -1.035 | -1.453 | -1.868 | -2.281 | -2.695 |
| R.C. | *Die Hard I* | 0.047 | -0.103 | -0.453 | -0.899 | -1.379 | -1.872 | -2.369 | -2.867 |
| 128 kbps | *Jurassic Park I* | 0.401 | 0.335 | 0.131 | -0.087 | -0.312 | -0.546 | -0.786 | -1.033 |
| | *Silence of the Lambs* | -0.077 | -0.229 | -0.557 | -1.091 | -1.739 | -2.429 | -3.126 | -3.820 |
| | *Star Wars IV* | -0.165 | -0.367 | -0.595 | -0.844 | -1.107 | -1.382 | -1.666 | -1.959 |
| | *Star Wars V* | -0.152 | -0.460 | -0.848 | -1.282 | -1.746 | -2.229 | -2.726 | -3.233 |
| | *The Firm* | -0.154 | -0.450 | -1.007 | -1.751 | -2.560 | -3.375 | -4.182 | -4.982 |
| | *Terminator I* | 0.173 | 0.020 | -0.342 | -0.761 | -1.193 | -1.626 | -2.059 | -2.488 |
| | *Total Recall* | 0.017 | -0.057 | -0.336 | -0.788 | -1.297 | -1.811 | -2.320 | -2.825 |
| | *Aladdin* | -0.040 | 0.106 | 0.235 | 0.254 | 0.190 | 0.074 | -0.072 | -0.235 |
| | *Cinderella* | 0.143 | 0.106 | -0.091 | -0.339 | -0.600 | -0.866 | -1.138 | -1.414 |
| | *Baseball with Comm* | -0.300 | -1.167 | -2.305 | -3.477 | -4.632 | -5.779 | -6.925 | -8.075 |
| | *Snowboard with Comm* | 0.166 | 0.250 | 0.284 | 0.294 | 0.287 | 0.263 | 0.224 | 0.173 |
| | *Oprah w/o Comm* | -0.191 | -0.622 | -1.269 | -2.049 | -2.893 | -3.764 | -4.645 | -5.528 |
| | *Tonight Show w/o Comm* | -0.001 | -0.233 | -0.627 | -1.078 | -1.547 | -2.024 | -2.504 | -2.986 |
| | *Lecture-Gupta* | 0.114 | 0.036 | -0.224 | -0.620 | -1.093 | -1.605 | -2.138 | -2.682 |
| | *Lecture-Reisslein* | 0.133 | 0.041 | -0.300 | -0.729 | -1.185 | -1.654 | -2.129 | -2.608 |
| QCIF | *Citizen Kane* | -0.057 | -0.106 | -0.158 | -0.228 | -0.326 | -0.457 | -0.617 | -0.797 |
| R.C. | *Die Hard I* | -0.024 | -0.043 | -0.054 | -0.059 | -0.061 | -0.061 | -0.060 | -0.059 |
| 256 kbps | *Jurassic Park I* | -0.047 | -0.093 | -0.141 | -0.195 | -0.254 | -0.322 | -0.396 | -0.477 |
| | *Silence of the Lambs* | -0.096 | -0.186 | -0.349 | -0.664 | -1.107 | -1.602 | -2.110 | -2.620 |
| | *Star Wars IV* | -0.080 | -0.150 | -0.221 | -0.289 | -0.356 | -0.422 | -0.485 | -0.548 |
| | *Star Wars V* | -0.073 | -0.146 | -0.220 | -0.297 | -0.375 | -0.457 | -0.541 | -0.629 |
| | *The Firm* | -0.061 | -0.119 | -0.175 | -0.230 | -0.285 | -0.342 | -0.400 | -0.462 |
| | *Terminator I* | -0.051 | -0.094 | -0.141 | -0.202 | -0.281 | -0.373 | -0.470 | -0.569 |
| | *Total Recall* | -0.062 | -0.117 | -0.170 | -0.222 | -0.276 | -0.334 | -0.396 | -0.460 |
| | *Aladdin* | -0.153 | -0.319 | -0.502 | -0.708 | -0.937 | -1.185 | -1.445 | -1.714 |
| | *Cinderella* | 0.019 | 0.001 | -0.180 | -0.518 | -0.942 | -1.402 | -1.876 | -2.355 |
| | *Baseball with Comm* | -0.078 | -0.162 | -0.247 | -0.334 | -0.425 | -0.523 | -0.629 | -0.744 |
| | *Snowboard with Comm* | -0.063 | -0.147 | -0.272 | -0.448 | -0.674 | -0.932 | -1.209 | -1.498 |
| | *Oprah w/o Comm* | -0.071 | -0.105 | -0.124 | -0.142 | -0.164 | -0.192 | -0.227 | -0.269 |
| | *Tonight Show w/o Comm* | -0.131 | -0.243 | -0.344 | -0.445 | -0.554 | -0.677 | -0.816 | -0.970 |
| | *Lecture-Gupta* | 0.011 | 0.017 | 0.014 | -0.008 | -0.052 | -0.113 | -0.188 | -0.272 |
| | *Lecture-Reisslein* | 0.054 | 0.092 | 0.119 | 0.132 | 0.127 | 0.103 | 0.058 | -0.004 |
| CIF | *Silence of the Lambs* | 1.044 | 1.924 | 2.724 | 3.481 | 4.212 | 4.925 | 5.628 | 6.324 |
| 040404. | *Terminator I* | 0.592 | 1.156 | 1.699 | 2.223 | 2.723 | 3.214 | 3.695 | 4.171 |
| No.R.C. | *Snowboard with Comm* | 0.482 | 0.938 | 1.379 | 1.812 | 2.239 | 2.664 | 3.085 | 3.504 |
| | *Oprah w/o Comm* | 0.640 | 1.271 | 1.898 | 2.534 | 3.179 | 3.828 | 4.463 | 5.095 |
| | *ParkingLot* | 0.604 | 1.222 | 1.842 | 2.443 | 3.046 | 3.617 | 4.140 | 4.669 |
| | *LectureHQ-Reisslein* | 0.514 | 1.012 | 1.503 | 1.993 | 2.476 | 2.968 | 3.455 | 3.939 |
| CIF | *Silence of the Lambs* | 0.944 | 1.829 | 2.656 | 3.437 | 4.187 | 4.917 | 5.635 | 6.343 |
| 040608. | *Terminator I* | 0.472 | 0.945 | 1.413 | 1.874 | 2.323 | 2.764 | 3.198 | 3.622 |
| No.R.C. | *Snowboard with Comm* | 0.486 | 0.947 | 1.397 | 1.844 | 2.293 | 2.746 | 3.200 | 3.656 |
| | *Oprah w/o Comm* | 0.537 | 1.070 | 1.591 | 2.092 | 2.565 | 3.006 | 3.419 | 3.811 |
| | *ParkingLot* | -0.347 | -0.651 | -0.920 | -1.166 | -1.399 | -1.624 | -1.846 | -2.069 |
| | *LectureHQ-Reisslein* | 0.473 | 0.924 | 1.354 | 1.768 | 2.165 | 2.541 | 2.901 | 3.246 |
| CIF | *Silence of the Lambs* | 0.327 | 0.715 | 1.126 | 1.524 | 1.966 | 2.404 | 2.815 | 3.217 |
| 060810. | *Terminator I* | 0.471 | 0.933 | 1.394 | 1.853 | 2.301 | 2.741 | 3.174 | 3.599 |
| No.R.C. | *Snowboard with Comm* | 0.478 | 0.944 | 1.400 | 1.856 | 2.315 | 2.779 | 3.247 | 3.717 |
| | *Oprah w/o Comm* | 0.568 | 1.127 | 1.675 | 2.227 | 2.778 | 3.320 | 3.854 | 4.381 |
| | *ParkingLot* | -0.306 | -0.274 | -0.066 | 0.234 | 0.583 | 0.961 | 1.354 | 1.755 |
| | *LectureHQ-Reisslein* | 0.464 | 0.902 | 1.322 | 1.726 | 2.111 | 2.469 | 2.810 | 3.133 |
| CIF | *Silence of the Lambs* | 0.910 | 1.772 | 2.590 | 3.374 | 4.135 | 4.882 | 5.619 | 6.347 |
| 101010. | *Terminator I* | 0.465 | 0.924 | 1.384 | 1.843 | 2.290 | 2.730 | 3.162 | 3.593 |
| No.R.C. | *Snowboard with Comm* | 0.473 | 0.939 | 1.397 | 1.855 | 2.317 | 2.785 | 3.258 | 3.734 |
| | *Oprah w/o Comm* | 0.568 | 1.120 | 1.658 | 2.198 | 2.733 | 3.255 | 3.768 | 4.274 |
| | *ParkingLot* | -0.362 | -0.672 | -0.938 | -1.180 | -1.413 | -1.644 | -1.876 | -2.111 |
| | *LectureHQ-Reisslein* | 0.456 | 0.894 | 1.317 | 1.727 | 2.116 | 2.475 | 2.815 | 3.133 |

Table 5: *continued*

| Enc. M. | Video | Multiscale Diagram, $\alpha_q$ for $q=0.5$ | $q=1$ | $q=1.5$ | $q=2$ | $q=2.5$ | $q=3$ | $q=3.5$ | $q=4$ |
|---|---|---|---|---|---|---|---|---|---|
| CIF | *Silence of the Lambs* | 0.898 | 1.721 | 2.508 | 3.272 | 4.021 | 4.761 | 5.493 | 6.219 |
| 101416. | *Terminator I* | 0.454 | 0.903 | 1.355 | 1.807 | 2.245 | 2.675 | 3.097 | 3.510 |
| No.R.C. | *Snowboard with Comm* | 0.475 | 0.939 | 1.399 | 1.862 | 2.331 | 2.806 | 3.286 | 3.769 |
| | *Oprah w/o Comm* | 0.552 | 1.113 | 1.673 | 2.219 | 2.745 | 3.251 | 3.741 | 4.220 |
| | *ParkingLot* | -0.358 | -0.650 | -0.892 | -1.110 | -1.321 | -1.534 | -1.751 | -1.971 |
| | *LectureHQ-Reisslein* | 0.459 | 0.892 | 1.311 | 1.715 | 2.082 | 2.431 | 2.748 | 3.048 |
| CIF | *Silence of the Lambs* | 0.725 | 1.559 | 2.339 | 3.076 | 3.792 | 4.497 | 5.197 | 5.895 |
| 242424. | *Terminator I* | 0.444 | 0.885 | 1.325 | 1.763 | 2.186 | 2.601 | 3.008 | 3.403 |
| No.R.C. | *Snowboard with Comm* | 0.529 | 1.057 | 1.579 | 2.091 | 2.594 | 3.085 | 3.568 | 4.035 |
| | *Oprah w/o Comm* | 0.515 | 1.045 | 1.589 | 2.137 | 2.683 | 3.224 | 3.758 | 4.288 |
| | *ParkingLot* | -0.265 | -0.499 | -0.716 | -0.927 | -1.141 | -1.359 | -1.583 | -1.813 |
| | *LectureHQ-Reisslein* | 0.437 | 0.895 | 1.350 | 1.792 | 2.216 | 2.621 | 3.009 | 3.383 |
| CIF | *Silence of the Lambs* | 0.483 | 0.976 | 1.476 | 1.988 | 2.509 | 3.033 | 3.555 | 4.071 |
| 303030. | *Terminator I* | 0.447 | 0.885 | 1.326 | 1.750 | 2.166 | 2.574 | 2.980 | 3.365 |
| No.R.C. | *Snowboard with Comm* | 0.521 | 1.044 | 1.561 | 2.070 | 2.569 | 3.063 | 3.537 | 4.012 |
| | *Oprah w/o Comm* | 0.509 | 1.027 | 1.555 | 2.087 | 2.619 | 3.149 | 3.675 | 4.197 |
| | *ParkingLot* | -0.274 | -0.543 | -0.805 | -1.063 | -1.321 | -1.581 | -1.845 | -2.113 |
| | *LectureHQ-Reisslein* | 0.449 | 0.914 | 1.377 | 1.827 | 2.260 | 2.673 | 3.067 | 3.445 |
| CIF | *Silence of the Lambs* | 0.488 | 0.975 | 1.469 | 1.973 | 2.487 | 3.005 | 3.522 | 4.035 |
| 64kbps | *Terminator I* | 0.446 | 0.884 | 1.320 | 1.747 | 2.162 | 2.569 | 2.975 | 3.360 |
| R.C. | *Snowboard with Comm* | 0.519 | 1.040 | 1.553 | 2.056 | 2.548 | 3.030 | 3.495 | 3.958 |
| | *Oprah w/o Comm* | 0.509 | 1.026 | 1.552 | 2.082 | 2.611 | 3.139 | 3.663 | 4.182 |
| | *ParkingLot* | -0.259 | -0.518 | -0.771 | -1.021 | -1.271 | -1.522 | -1.777 | -2.036 |
| | *LectureHQ-Reisslein* | 0.447 | 0.906 | 1.366 | 1.815 | 2.247 | 2.661 | 3.057 | 3.437 |
| CIF | *Silence of the Lambs* | 0.488 | 0.975 | 1.469 | 1.974 | 2.488 | 3.006 | 3.523 | 4.035 |
| 128kbps | *Terminator I* | 0.446 | 0.884 | 1.320 | 1.747 | 2.162 | 2.569 | 2.975 | 3.360 |
| R.C. | *Snowboard with Comm* | 0.519 | 1.040 | 1.554 | 2.056 | 2.548 | 3.031 | 3.495 | 3.958 |
| | *Oprah w/o Comm* | 0.509 | 1.025 | 1.552 | 2.082 | 2.611 | 3.139 | 3.662 | 4.182 |
| | *ParkingLot* | -0.259 | -0.517 | -0.771 | -1.021 | -1.270 | -1.522 | -1.777 | -2.035 |
| | *LectureHQ-Reisslein* | 0.447 | 0.906 | 1.365 | 1.812 | 2.243 | 2.655 | 3.048 | 3.426 |
| CIF | *Silence of the Lambs* | 0.515 | 1.069 | 1.559 | 1.963 | 2.307 | 2.618 | 2.910 | 3.193 |
| 256kbps | *Terminator I* | 0.448 | 0.885 | 1.321 | 1.748 | 2.162 | 2.570 | 2.976 | 3.361 |
| R.C. | *Snowboard with Comm* | 0.519 | 1.038 | 1.545 | 2.033 | 2.502 | 2.955 | 3.396 | 3.829 |
| | *Oprah w/o Comm* | 0.503 | 1.002 | 1.488 | 1.957 | 2.383 | 2.777 | 3.146 | 3.502 |
| | *ParkingLot* | -0.247 | -0.498 | -0.748 | -0.997 | -1.246 | -1.497 | -1.750 | -2.007 |
| | *LectureHQ-Reisslein* | 0.043 | -0.016 | -0.299 | -0.735 | -1.219 | -1.715 | -2.213 | -2.709 |
| CIF | *ParkingLot* | -0.646 | -1.270 | -1.879 | -2.486 | -3.095 | -3.709 | -4.327 | -4.948 |
| 512kbps | *LectureHQ-Reisslein* | -0.057 | -0.052 | -0.017 | 0.030 | 0.077 | 0.115 | 0.142 | 0.156 |
| R.C. | *Silence of the Lambs* | | | | | | | | |
| CIF | *ParkingLot* | -0.063 | -0.159 | -0.277 | -0.395 | -0.527 | -0.661 | -0.790 | -0.918 |
| 1024kbps | *LectureHQ-Reisslein* | -0.033 | -0.036 | -0.008 | 0.035 | 0.082 | 0.125 | 0.162 | 0.191 |
| R.C. | *Silence of the Lambs* | | | | | | | | |

Figures 11 and 12 give the multiscale diagrams and the linear multiscale diagrams. From the linear multiscale diagrams in Figure 12, we observe that $h_q$ typically does not change significantly (compared to the error bars of the individual $h_q$ estimates) as a function of $q$. This indicates that the video is mono-fractal, i.e., does not exhibit a significant multi-fractal behavior.

# 3 Analysis of Video Quality

In our analysis of the video quality we focus on the peak signal to noise ratio (PSNR) and the mean squared error (MSE), which are formally defined in the Appendix of Part 1 of this

technical report. We are aware that these measures do not completely capture the many facets of video quality, however, analyzing a large number of video sequences for so many encoding modes (different qualities both with and without rate control) subjectively becomes impractical. Moreover, recent studies have found that the PSNR is as good a measure of video quality as other, more sophisticated, objective quality metrics [5]. As the PSNR and MSE are well-defined only for the luminance (Y) component [6] and since the human visual system is more sensitive to small degrees of the luminance variation, we focus on the luminance PSNR values $Q_n^Y,\ n = 0, \ldots, N-1$, in our analysis. For convenience we denote $Q_n$ for $Q_n^Y$, and $M_n$ for $p^2/10^{(Q_n/10)}$.

Table 6 gives the average quality $\bar{Q}$, the coefficient of quality variation $CoQV$, the alternative coefficient of quality variation $CoQV'$, and the quality range $Q_{\min}^{\max}$ for the video frames, as defined in the Appendix of Part 1. The table also gives the coefficients of variation $CoQV^{(G)}$ and $CoQV'^{(G)}$, and the quality range $Q_{\min}^{\max(G)}$ for the GoP aggregation. We observe that the average quality obtained is typically $36.0 - 37.0$ dB for high quality encodings, $28.0 - 31.9$ dB for medium quality and $24.0 - 27.9$ dB for low quality. It is interesting to note, from Tables 1 and 6, that videos which have the highest compression ratios for a given encoding mode have the highest average qualities, and videos with smaller compression ratios have smaller average qualities. This result would be quite startling if the PSNR were an accurate absolute gauge of overall quality that could be used to compare the quality of different encoded video sequences. The average PSNR, however, can not be used as an absolute measure for comparing the quality of different videos. The average PSNR for one video encoded with a particular set of quantization parameters is not comparable to another video's average PSNR encoded with the same set of quantization parameters, because the inter-relation of the average PSNR of a video encoding depends on the video content, the visual composition of the scenes, the lighting, etc. We note, however, that the average PSNR does allow for a rough comparison of the qualities of a given video for different encoding modes. Further study of this issue will be done in the future.

We observe that the alternative coefficient of quality variation ($CoQV'^{(G)}$) and the quality range ($Q_{\min}^{\max(G)}$), are smaller for the GoP aggregation level of $a = 12$ for all sequences. From an analysis of the terse video trace files, not shown here, we conclude that decoded I frames give the highest relative quality followed by P and then B frames. Thus, the number of frames in a GoP — which determines the number of I frames in a video sequence — and the GoP structure — which determines the number of P and B frames in a video sequence — can have a major impact on the decoded video quality for a given quantization level. This also effects the compression ratios; hence there is a trade-off between the two.

Table 6: Overview of quality statistics of single-layer traces

| | | Frame Level | | | | GoP level | | |
|---|---|---|---|---|---|---|---|---|
| Enc. M. | Video | $\bar{Q}$ dB | $CoQV$ | $CoQV'$ | $Q_{\min}^{\max}$ dB | $CoQV^{(G)}$ | $CoQV'^{(G)}$ | $Q_{\min}^{\max(G)}$ |
| QCIF | *Citizen Kane* | 37.638 | 0.491 | 0.030 | 31.760 | 0.267 | 0.026 | 17.079 |
| H.Q. | *Die Hard I* | 36.495 | 13.646 | 0.021 | 49.411 | 3.934 | 0.015 | 36.086 |
| No R.C. | *Jurassic Park I* | 36.561 | 0.197 | 0.026 | 14.436 | 0.158 | 0.020 | 6.003 |
| | *Silence of the Lambs* | 37.104 | 0.186 | 0.023 | 18.686 | 0.160 | 0.020 | 12.591 |
| | *Star Wars IV* | 37.073 | 0.221 | 0.034 | 22.776 | 0.194 | 0.030 | 12.008 |
| | *Star Wars V* | 35.986 | 17.011 | 0.051 | 50.579 | 4.949 | 0.048 | 38.759 |
| | *The Firm* | 36.717 | 0.162 | 0.020 | 17.326 | 0.121 | 0.014 | 7.939 |
| | *Terminator I* | 37.045 | 0.670 | 0.030 | 33.085 | 0.295 | 0.024 | 23.851 |
| | *Total Recall* | 36.643 | 0.182 | 0.020 | 27.913 | 0.116 | 0.014 | 13.321 |
| | *Aladdin* | 36.026 | 0.163 | 0.024 | 13.532 | 0.109 | 0.016 | 8.071 |
| | *Cinderella* | 36.154 | 12.563 | 0.021 | 40.847 | 3.634 | 0.014 | 29.675 |
| | *Baseball with Comm* | 35.990 | 0.204 | 0.025 | 42.467 | 0.123 | 0.018 | 12.091 |
| | *Snowboard with Comm* | 36.302 | 0.521 | 0.029 | 34.272 | 0.239 | 0.021 | 21.041 |
| | *Oprah w/o Comm* | 35.688 | 0.164 | 0.023 | 13.260 | 0.111 | 0.015 | 4.424 |
| | *Tonight Show w/o Comm* | 37.674 | 0.594 | 0.130 | 22.366 | 0.574 | 0.129 | 12.518 |
| | *Lecture-Gupta* | 36.215 | 0.164 | 0.023 | 8.609 | 0.105 | 0.014 | 5.865 |
| | *Lecture-Reisslein* | 35.994 | 0.700 | 0.046 | 33.754 | 0.354 | 0.042 | 25.634 |
| QCIF | *Jurassic Park I* | 30.782 | 0.353 | 0.054 | 18.984 | 0.336 | 0.052 | 12.470 |
| M.–L.Q | *Star Wars IV* | 32.453 | 0.907 | 0.050 | 35.839 | 0.401 | 0.048 | 22.482 |
| No R.C. | *The Firm* | 31.752 | 0.362 | 0.047 | 16.458 | 0.346 | 0.045 | 10.802 |
| | *Tonight Show w/o Comm* | 31.831 | 0.616 | 0.165 | 19.217 | 0.608 | 0.165 | 15.940 |
| QCIF | *Citizen Kane* | 31.050 | 0.651 | 0.067 | 34.129 | 0.462 | 0.062 | 21.777 |
| M.Q. | *Die Hard I* | 30.786 | 3.685 | 0.051 | 43.268 | 1.104 | 0.043 | 29.799 |
| No R.C. | *Jurassic Park I* | 29.458 | 0.465 | 0.069 | 22.130 | 0.419 | 0.063 | 15.633 |
| | *Silence of the Lambs* | 31.888 | 0.577 | 0.064 | 24.458 | 0.543 | 0.061 | 16.900 |
| | *Star Wars IV* | 31.378 | 1.251 | 0.060 | 38.338 | 0.518 | 0.054 | 23.540 |
| | *Star Wars V* | 29.980 | 0.495 | 0.084 | 29.725 | 0.436 | 0.079 | 18.598 |
| | *The Firm* | 30.659 | 0.490 | 0.061 | 17.297 | 0.450 | 0.057 | 12.730 |
| | *Terminator I* | 30.201 | 0.973 | 0.068 | 38.452 | 0.471 | 0.059 | 25.788 |
| | *Total Recall* | 30.628 | 0.523 | 0.055 | 30.171 | 0.360 | 0.047 | 16.189 |
| | *Aladdin* | 28.887 | 0.542 | 0.058 | 31.839 | 0.335 | 0.048 | 15.913 |
| | *Cinderella* | 29.825 | 2.939 | 0.053 | 40.574 | 0.902 | 0.044 | 28.950 |
| | *Baseball with Comm* | 29.650 | 0.472 | 0.060 | 53.192 | 0.340 | 0.053 | 18.248 |
| | *Snowboard with Comm* | 28.986 | 0.483 | 0.074 | 28.438 | 0.412 | 0.065 | 15.010 |
| | *Oprah w/o Comm* | 28.471 | 0.326 | 0.053 | 23.833 | 0.282 | 0.045 | 12.626 |
| | *Tonight Show w/o Comm* | 30.678 | 0.688 | 0.185 | 21.046 | 0.654 | 0.184 | 18.843 |
| | *Lecture-Gupta* | 28.360 | 0.321 | 0.055 | 18.180 | 0.257 | 0.041 | 14.984 |
| | *Lecture-Reisslein* | 27.990 | 0.505 | 0.133 | 29.405 | 0.453 | 0.129 | 21.894 |
| QCIF | *Jurassic Park I* | 26.535 | 0.438 | 0.076 | 22.388 | 0.427 | 0.074 | 17.069 |
| H.–M.Q. | *Star Wars IV* | 28.745 | 1.097 | 0.071 | 36.704 | 0.537 | 0.069 | 23.464 |
| No R.C. | *The Firm* | 27.745 | 1.099 | 0.076 | 18.258 | 1.102 | 0.075 | 14.349 |
| | *Tonight Show w/o Comm* | 27.131 | 0.662 | 0.231 | 23.248 | 0.657 | 0.231 | 21.299 |
| QCIF | *Citizen Kane* | 26.910 | 0.532 | 0.082 | 33.394 | 0.472 | 0.081 | 22.828 |
| L.Q. | *Die Hard I* | 27.132 | 1.618 | 0.062 | 38.709 | 0.577 | 0.059 | 26.407 |
| No R.C. | *Jurassic Park I* | 25.681 | 0.447 | 0.080 | 22.461 | 0.439 | 0.078 | 17.653 |
| | *Silence of the Lambs* | 28.446 | 0.679 | 0.083 | 21.224 | 0.666 | 0.082 | 18.621 |
| | *Star Wars IV* | 27.892 | 1.006 | 0.075 | 34.876 | 0.546 | 0.073 | 23.119 |
| | *Star Wars V* | 26.604 | 0.549 | 0.103 | 25.701 | 0.532 | 0.101 | 17.965 |
| | *The Firm* | 26.901 | 0.559 | 0.083 | 22.208 | 0.548 | 0.081 | 15.371 |
| | *Terminator I* | 26.457 | 0.746 | 0.084 | 36.370 | 0.493 | 0.080 | 26.615 |
| | *Total Recall* | 27.029 | 0.434 | 0.066 | 25.233 | 0.388 | 0.064 | 15.572 |
| | *Aladdin* | 25.335 | 0.471 | 0.077 | 27.398 | 0.412 | 0.074 | 14.735 |
| | *Cinderella* | 26.094 | 1.303 | 0.065 | 39.998 | 0.519 | 0.063 | 28.318 |
| | *Baseball with Comm* | 26.303 | 0.444 | 0.078 | 37.139 | 0.398 | 0.074 | 18.972 |
| | *Snowboard with Comm* | 25.177 | 0.499 | 0.093 | 29.342 | 0.479 | 0.090 | 16.379 |
| | *Oprah w/o Comm* | 25.248 | 0.305 | 0.053 | 26.889 | 0.295 | 0.051 | 16.180 |
| | *Tonight Show w/o Comm* | 26.214 | 0.680 | 0.256 | 24.988 | 0.675 | 0.256 | 23.386 |
| | *Lecture-Gupta* | 23.846 | 0.314 | 0.065 | 22.052 | 0.307 | 0.064 | 20.034 |
| | *Lecture-Reisslein* | 24.057 | 0.523 | 0.160 | 28.123 | 0.517 | 0.159 | 21.948 |
| QCIF | *Citizen Kane* | 27.383 | 0.685 | 0.111 | 41.183 | 1.038 | 0.086 | 21.405 |

Table 6: *continued*

| | | Frame Level | | | | GoP level | | |
|---|---|---|---|---|---|---|---|---|
| Enc. M. | Video | $\bar{Q}$ dB | $CoQV$ | $CoQV'$ | $Q_{\min}^{\max}$ dB | $CoQV^{(G)}$ | $CoQV'^{(G)}$ | $Q_{\min}^{\max(G)}$ |
| R.C. | *Die Hard I* | 27.025 | 1.585 | 0.064 | 39.369 | 1.498 | 0.060 | 37.237 |
| 64 kbps | *Jurassic Park I* | 25.585 | 0.451 | 0.085 | 25.516 | 0.915 | 0.092 | 21.269 |
| | *Silence of the Lambs* | 28.926 | 0.830 | 0.108 | 29.721 | 1.297 | 0.074 | 31.059 |
| | *Star Wars IV* | 27.935 | 1.053 | 0.081 | 48.171 | 0.868 | 0.073 | 28.030 |
| | *Star Wars V* | 26.512 | 0.557 | 0.105 | 43.121 | 0.773 | 0.108 | 32.013 |
| | *The Firm* | 27.041 | 0.627 | 0.099 | 22.591 | 0.905 | 0.077 | 18.442 |
| | *Terminator I* | 26.355 | 0.770 | 0.085 | 44.135 | 0.813 | 0.092 | 28.454 |
| | *Total Recall* | 26.957 | 0.446 | 0.071 | 36.817 | 0.656 | 0.067 | 17.391 |
| | *Aladdin* | 25.221 | 0.478 | 0.078 | 39.523 | 0.718 | 0.084 | 18.341 |
| | *Cinderella* | 25.981 | 1.270 | 0.066 | 39.695 | 1.204 | 0.076 | 30.015 |
| | *Baseball with Comm* | 26.221 | 0.448 | 0.080 | 37.664 | 0.594 | 0.071 | 20.933 |
| | *Snowboard with Comm* | 25.052 | 0.498 | 0.094 | 26.402 | 0.745 | 0.104 | 23.764 |
| | *Oprah w/o Comm* | 25.145 | 0.307 | 0.054 | 32.042 | 0.548 | 0.073 | 17.812 |
| | *Tonight Show w/o Comm* | 26.539 | 0.741 | 0.309 | 31.522 | 1.000 | 0.239 | 29.026 |
| | *Lecture-Gupta* | 23.693 | 0.315 | 0.066 | 22.177 | 0.543 | 0.062 | 20.274 |
| | *Lecture-Reisslein* | 23.912 | 0.522 | 0.158 | 27.713 | 0.650 | 0.155 | 29.749 |
| QCIF | *Citizen Kane* | 30.773 | 1.272 | 0.108 | 44.167 | 1.096 | 0.106 | 24.928 |
| R.C. | *Die Hard I* | 29.823 | 3.021 | 0.087 | 54.425 | 1.071 | 0.083 | 33.983 |
| 128 kbps | *Jurassic Park I* | 28.117 | 0.792 | 0.109 | 24.161 | 0.777 | 0.106 | 21.239 |
| | *Silence of the Lambs* | 31.795 | 1.330 | 0.097 | 33.185 | 1.311 | 0.095 | 29.205 |
| | *Star Wars IV* | 30.978 | 1.769 | 0.094 | 48.617 | 1.014 | 0.090 | 30.358 |
| | *Star Wars V* | 28.801 | 0.864 | 0.130 | 38.917 | 0.830 | 0.127 | 30.477 |
| | *The Firm* | 29.928 | 0.980 | 0.101 | 21.811 | 0.959 | 0.099 | 18.229 |
| | *Terminator I* | 28.380 | 0.931 | 0.119 | 44.868 | 0.764 | 0.114 | 27.924 |
| | *Total Recall* | 29.668 | 0.766 | 0.092 | 36.258 | 0.686 | 0.088 | 17.338 |
| | *Aladdin* | 26.120 | 0.641 | 0.105 | 38.624 | 0.575 | 0.101 | 16.320 |
| | *Cinderella* | 28.075 | 2.076 | 0.097 | 49.343 | 0.861 | 0.092 | 29.716 |
| | *Baseball with Comm* | 28.216 | 0.664 | 0.094 | 53.984 | 0.591 | 0.089 | 20.833 |
| | *Snowboard with Comm* | 26.126 | 0.668 | 0.123 | 41.135 | 0.640 | 0.119 | 20.451 |
| | *Oprah w/o Comm* | 27.082 | 0.526 | 0.078 | 30.006 | 0.510 | 0.076 | 18.064 |
| | *Tonight Show w/o Comm* | 29.173 | 0.987 | 0.282 | 31.345 | 0.973 | 0.282 | 29.179 |
| | *Lecture-Gupta* | 26.450 | 0.578 | 0.078 | 29.221 | 0.557 | 0.073 | 20.866 |
| | *Lecture-Reisslein* | 25.809 | 0.708 | 0.183 | 36.308 | 0.695 | 0.182 | 29.105 |
| QCIF | *Citizen Kane* | 33.458 | 1.140 | 0.091 | 39.732 | 0.552 | 0.109 | 24.207 |
| R.C. | *Die Hard I* | 32.361 | 5.307 | 0.068 | 58.075 | 0.511 | 0.060 | 27.032 |
| 256 kbps | *Jurassic Park I* | 30.563 | 0.939 | 0.096 | 23.429 | 0.378 | 0.083 | 20.902 |
| | *Silence of the Lambs* | 33.824 | 1.398 | 0.078 | 36.115 | 0.791 | 0.106 | 18.514 |
| | *Star Wars IV* | 33.338 | 1.063 | 0.078 | 44.470 | 0.525 | 0.079 | 22.974 |
| | *Star Wars V* | 30.995 | 0.807 | 0.112 | 38.956 | 0.483 | 0.103 | 17.925 |
| | *The Firm* | 32.231 | 0.942 | 0.082 | 23.975 | 0.560 | 0.097 | 16.938 |
| | *Terminator I* | 31.157 | 0.937 | 0.102 | 46.188 | 0.441 | 0.081 | 25.758 |
| | *Total Recall* | 32.147 | 0.722 | 0.074 | 40.134 | 0.339 | 0.068 | 15.644 |
| | *Aladdin* | 28.461 | 0.827 | 0.093 | 41.964 | 0.371 | 0.075 | 15.004 |
| | *Cinderella* | 30.472 | 3.487 | 0.083 | 41.801 | 0.462 | 0.064 | 28.030 |
| | *Baseball with Comm* | 30.395 | 0.639 | 0.078 | 51.875 | 0.350 | 0.077 | 19.171 |
| | *Snowboard with Comm* | 28.692 | 0.788 | 0.111 | 38.684 | 0.432 | 0.090 | 15.592 |
| | *Oprah w/o Comm* | 28.850 | 0.536 | 0.077 | 29.715 | 0.247 | 0.052 | 16.399 |
| | *Tonight Show w/o Comm* | 31.703 | 1.045 | 0.239 | 30.929 | 0.689 | 0.309 | 28.903 |
| | *Lecture-Gupta* | 28.479 | 0.536 | 0.072 | 26.107 | 0.244 | 0.065 | 20.087 |
| | *Lecture-Reisslein* | 27.794 | 0.655 | 0.157 | 37.269 | 0.464 | 0.158 | 20.260 |
| CIF | *Silence of the Lambs* | 37.896 | 1.197 | 0.023 | 15.978 | 1.212 | 0.02 | 13.809 |
| 040404. | *Terminator I* | 38.009 | 1.1 | 0.028 | 33.403 | 1.183 | 0.023 | 20.934 |
| No.R.C. | *Snowboard with Comm* | 37.025 | 1.198 | 0.029 | 18.211 | 1.225 | 0.023 | 9.590 |
| | *Oprah w/o Comm* | 36.24 | 1.221 | 0.022 | 4.986 | 1.262 | 0.015 | 4.261 |
| | *ParkingLot* | 37.039 | 1.232 | 0.020 | 12.739 | 1.317 | 0.009 | 5.064 |
| | *LectureHQ-Reisslein* | 38.303 | 1.218 | 0.017 | 4.451 | 1.248 | 0.012 | 3.017 |
| CIF | *Silence of the Lambs* | 35.842 | 1.108 | 0.046 | 21.393 | 1.13 | 0.036 | 15.650 |
| 040608. | *Terminator I* | 35.213 | 1.033 | 0.055 | 37.597 | 1.124 | 0.039 | 22.261 |
| No.R.C. | *Snowboard with Comm* | 33.752 | 1.129 | 0.058 | 27.126 | 1.181 | 0.035 | 11.886 |
| | *Oprah w/o Comm* | 32.437 | 1.138 | 0.063 | 10.367 | 1.199 | 0.035 | 8.295 |

Table 6: *continued*

| | | Frame Level | | | | GoP level | | |
|---|---|---|---|---|---|---|---|---|
| Enc. M. | Video | $\bar{Q}$ dB | $CoQV$ | $CoQV'$ | $Q_{\min}^{\max}$ dB | $CoQV^{(G)}$ | $CoQV'^{(G)}$ | $Q_{\min}^{\max(G)}$ |
| | *ParkingLot* | 33.453 | 1.152 | 0.055 | 18.518 | 1.246 | 0.020 | 6.428 |
| | *LectureHQ-Reisslein* | 36.061 | 1.166 | 0.036 | 9.320 | 1.221 | 0.018 | 4.886 |
| CIF | *Silence of the Lambs* | 35.023 | 1.094 | 0.049 | 17.126 | 1.106 | 0.045 | 14.369 |
| 060810. | *Terminator I* | 34.042 | 0.955 | 0.056 | 34.355 | 1.074 | 0.045 | 22.098 |
| No.R.C. | *Snowboard with Comm* | 32.601 | 1.13 | 0.054 | 22.813 | 1.164 | 0.042 | 12.358 |
| | *Oprah w/o Comm* | 31.312 | 1.162 | 0.052 | 10.923 | 1.197 | 0.039 | 9.589 |
| | *ParkingLot* | 31.720 | 1.173 | 0.046 | 19.774 | 1.213 | 0.029 | 6.801 |
| | *LectureHQ-Reisslein* | 34.917 | 1.178 | 0.031 | 9.045 | 1.210 | 0.021 | 5.627 |
| CIF | *Silence of the Lambs* | 34.337 | 1.1 | 0.05 | 15.962 | 1.105 | 0.049 | 14.594 |
| 101010. | *Terminator I* | 33.377 | 0.935 | 0.054 | 34.545 | 1.061 | 0.049 | 22.844 |
| No.R.C. | *Snowboard with Comm* | 32.004 | 1.135 | 0.049 | 26.308 | 1.161 | 0.045 | 12.456 |
| | *Oprah w/o Comm* | 30.802 | 1.215 | 0.035 | 10.827 | 1.223 | 0.033 | 9.842 |
| | *ParkingLot* | 30.989 | 1.243 | 0.027 | 17.658 | 1.269 | 0.022 | 6.137 |
| | *LectureHQ-Reisslein* | 33.626 | 1.189 | 0.028 | 7.345 | 1.197 | 0.026 | 5.979 |
| CIF | *Silence of the Lambs* | 33.423 | 1.06 | 0.063 | 19.029 | 1.069 | 0.06 | 16.354 |
| 101416. | *Terminator I* | 31.891 | 0.925 | 0.069 | 35.746 | 1.05 | 0.06 | 24.889 |
| No.R.C. | *Snowboard with Comm* | 30.483 | 1.109 | 0.065 | 27.492 | 1.137 | 0.057 | 12.469 |
| | *Oprah w/o Comm* | 29.679 | 1.183 | 0.046 | 13.288 | 1.202 | 0.041 | 11.985 |
| | *ParkingLot* | 29.305 | 1.163 | 0.050 | 25.563 | 1.196 | 0.037 | 7.342 |
| | *LectureHQ-Reisslein* | 32.824 | 1.176 | 0.034 | 10.257 | 1.195 | 0.028 | 7.299 |
| CIF | *Silence of the Lambs* | 31.384 | 1.044 | 0.078 | 19.35 | 1.05 | 0.075 | 17.446 |
| 242424. | *Terminator I* | 29.635 | 0.978 | 0.08 | 34.17 | 1.084 | 0.073 | 22.825 |
| No.R.C. | *Snowboard with Comm* | 28.128 | 1.115 | 0.077 | 27.72 | 1.128 | 0.074 | 12.406 |
| | *Oprah w/o Comm* | 27.907 | 1.226 | 0.037 | 14.79 | 1.233 | 0.035 | 13.661 |
| | *ParkingLot* | 25.975 | 1.248 | 0.041 | 24.081 | 1.259 | 0.039 | 7.921 |
| | *LectureHQ-Reisslein* | 29.358 | 1.175 | 0.041 | 10.349 | 1.177 | 0.041 | 8.588 |
| CIF | *Silence of the Lambs* | 30.677 | 1.034 | 0.083 | 21.594 | 1.04 | 0.081 | 19.161 |
| 303030. | *Terminator I* | 28.772 | 1.002 | 0.085 | 33.798 | 1.092 | 0.078 | 22.608 |
| No.R.C. | *Snowboard with Comm* | 27.214 | 1.114 | 0.084 | 25.721 | 1.125 | 0.08 | 13.130 |
| | *Oprah w/o Comm* | 27.254 | 1.224 | 0.039 | 15.139 | 1.232 | 0.037 | 14.234 |
| | *ParkingLot* | 24.849 | 1.255 | 0.046 | 26.193 | 1.264 | 0.043 | 8.416 |
| | *LectureHQ-Reisslein* | 28.315 | 1.175 | 0.044 | 10.779 | 1.177 | 0.044 | 8.966 |
| CIF | *Silence of the Lambs* | 30.591 | 1.033 | 0.084 | 21.553 | 1.039 | 0.081 | 19.117 |
| R.C. | *Terminator I* | 28.665 | 1.002 | 0.086 | 33.675 | 1.093 | 0.079 | 22.660 |
| 64kbps | *Snowboard with Comm* | 27.096 | 1.114 | 0.085 | 26.082 | 1.125 | 0.081 | 13.058 |
| | *Oprah w/o Comm* | 27.17 | 1.224 | 0.039 | 15.39 | 1.232 | 0.037 | 14.380 |
| | *ParkingLot* | 24.708 | 1.257 | 0.046 | 23.604 | 1.266 | 0.044 | 8.422 |
| | *LectureHQ-Reisslein* | 28.170 | 1.175 | 0.045 | 10.756 | 1.177 | 0.044 | 8.843 |
| CIF | *Silence of the Lambs* | 30.595 | 1.033 | 0.084 | 21.553 | 1.039 | 0.081 | 19.117 |
| R.C. | *Terminator I* | 28.665 | 1.002 | 0.086 | 33.675 | 1.093 | 0.079 | 22.660 |
| 128kbps | *Snowboard with Comm* | 27.096 | 1.114 | 0.085 | 26.082 | 1.125 | 0.081 | 13.058 |
| | *Oprah w/o Comm* | 27.17 | 1.224 | 0.039 | 15.39 | 1.232 | 0.037 | 14.380 |
| | *ParkingLot* | 24.708 | 1.257 | 0.046 | 23.604 | 1.266 | 0.044 | 8.422 |
| | *LectureHQ-Reisslein* | 28.170 | 1.175 | 0.045 | 10.744 | 1.177 | 0.044 | 8.738 |
| CIF | *Silence of the Lambs* | 31.095 | 1.011 | 0.102 | 28.151 | 1.017 | 0.099 | 19.117 |
| R.C. | *Terminator I* | 28.671 | 1.001 | 0.087 | 33.675 | 1.092 | 0.08 | 22.660 |
| 256kbps | *Snowboard with Comm* | 27.105 | 1.113 | 0.085 | 26.082 | 1.124 | 0.081 | 13.058 |
| | *Oprah w/o Comm* | 27.295 | 1.203 | 0.046 | 16.322 | 1.209 | 0.044 | 14.884 |
| | *ParkingLot* | 24.711 | 1.256 | 0.046 | 23.604 | 1.265 | 0.044 | 8.917 |
| | *LectureHQ-Reisslein* | 31.626 | 1.082 | 0.057 | 16.819 | 1.086 | 0.055 | 12.107 |
| CIF | *ParkingLot* | 25.916 | 1.109 | 0.103 | 31.281 | 1.116 | 0.097 | 11.652 |
| R.C. | *LectureHQ-Reisslein* | 33.879 | 1.096 | 0.045 | 16.467 | 1.105 | 0.042 | 12.460 |
| 512kbps | *Silence of the Lambs* | | | | | | | |
| CIF | *ParkingLot* | 28.797 | 1.040 | 0.096 | 30.631 | 1.054 | 0.089 | 13.807 |
| R.C. | *LectureHQ-Reisslein* | 35.772 | 1.113 | 0.037 | 17.747 | 1.130 | 0.033 | 11.243 |
| 1024kbps | *Silence of the Lambs* | | | | | | | |

Figure 13 gives the video frame qualities $Q_n$ (in dB) as a function of the frame number $n$.

Figure 14 gives the histogram of the frame qualities $Q_n$. We observe from Figures 13 and 14 that video encodings without rate control have less variability in frame quality, than videos with rate control. The rate-controlled video sequences tend to have more variability in their quality because rate control sacrifices quality to make the bit rate nearly constant (at the GoP time scale with TM5 rate control).

Figure 15 gives the MSE autocorrelation coefficient $\rho_M(k)$ as a function of lag $k$ (in frames). The I frames, overall, have a smaller MSE than the P and B frames for a given GoP. This results in periodic spikes with a frequency of a 12 frame lag, which is equal to GoP size in frames.

Figure 16 gives the MSE autocorrelation coefficient $\rho_M^{(G)}(k)$ as a function of lag $k$ (in GoPs). We observe quite significant autocorrelation for large lags in the MSE of all encodings. While MSE autocorrelation functions for the *Jurassic Park I* encodings appear to initially drop off exponentially, they flatten out around a level of 0.2 for large lags. The MSE autocorrelations for *Silence of the Lambs* are especially high for large lags. Overall, the MSE autocorrelations indicate significant correlations in the qualities of successive frames.

Figure 17 gives scatter plots of the tuples $(X_n,\ Q_n),\ n = 0, \ldots, N-1$, where I frames are plotted in red, P frames are plotted in green, and B frames are plotted in blue. Figure 18 gives scatter plots of the tuples $(X_n^{(G)},\ Q_n^{(G)}),\ n = 0, \ldots, N/G-1$, i.e., the frame sizes and qualities averaged over a GoP. From the scatter plots in Figures 17 and 18, we observe, as before, that video encodings without rate control have less variability in their frame sizes than videos with rate control. (To see this, take note of the different scales on the x-axis.) The outliers in the rate-controlled sequences are an order of magnitude larger in size than the smaller frames of these traces. There are few of them but they have a large effect on the overall statistics of the sequence, leading to the observation made earlier that there is more variability in the traces of rate-controlled sequences. We also observe, that the rate-controlled video sequences tend to have more variability in their quality with a nearly constant GoP size, while videos without rate control tend to have less variability in their average quality with more variability in their GoP size.

# 4 Correlation Between Frame Sizes and Qualities

Table 7 gives the size-MSE quality correlation coefficient $\rho_{XM}$ and the size-PSNR quality correlation coefficient $\rho_{XQ}$, as well as the corresponding correlation coefficients $\rho_{XM}^{(G)}$ and $\rho_{XQ}^{(G)}$ for the GoP aggregation. Before we study these correlations in detail, note the inverse relationship between PSNR quality and MSE. The smaller the PSNR, the larger the MSE and vice versa. This implies that a positive $\rho_{XQ}$ typically corresponds to a negative $\rho_{XM}$ and vice versa. For

consistency we focus on $\rho_{XQ}$ in the following discussion.

For the frame level of the encodings without rate control, we observe the general trend that the magnitude of $\rho_{XQ}$ increases as the quality decreases. Also, whereas at the high quality level there is a mix of positive and negative $\rho_{XQ}$, at the low quality level all $\rho_{XQ}$ values are negative.

For encodings with rate control we observe the reverse trend. The magnitude of $\rho_{XQ}$ increases as the target bit rate (and thus video quality) increases. Also, for the 64 kbps target bit rate encodings, all $\rho_{XQ}$ are negative, whereas for the 128 and 256 kbps target bit rate encodings all $\rho_{XQ}$ are positive.

Interestingly, the correlations of the encodings without rate control at the GoP level contrast the correlations at the frame level. All $\rho_{XQ}^{(G)}$ are negative with magnitudes that generally increase with increasing quality level.

The quality-size correlations of the encodings with rate control — at the GoP level — are negative for 64 kbps, mixed for 128 kbps, and positive for 256 kbps.

These interesting observations, about the behavior of the frame size–quality correlations, are difficult to explain and interpret based on the frame sizes and qualities alone. We believe that video content characteristics need to be considered as well to understand the fundamental phenomenon underlying the observations made above. We will conduct such a study considering jointly frame sizes, qualities, and visual content in the future.

Table 7: Correlation between quality and traffic for single-layer traces

| Enc. M. | Video | Frame Level $\rho_{XM}$ | Frame Level $\rho_{XQ}$ | GoP level $\rho^{(G)}_{XM}$ | GoP level $\rho^{(G)}_{XQ}$ |
|---|---|---|---|---|---|
| QCIF | *Citizen Kane* | 0.120 | -0.182 | 0.617 | -0.721 |
| No R.C. | *Die Hard I* | 0.001 | 0.175 | 0.026 | -0.578 |
| H.Q. | *Jurassic Park I* | 0.101 | -0.057 | 0.722 | -0.698 |
| | *Silence of the Lambs* | 0.257 | -0.206 | 0.770 | -0.719 |
| | *Star Wars IV* | 0.077 | -0.082 | 0.609 | -0.534 |
| | *Star Wars V* | 0.005 | -0.248 | 0.033 | -0.587 |
| | *The Firm* | 0.006 | 0.060 | 0.736 | -0.718 |
| | *Terminator I* | 0.028 | -0.055 | 0.298 | -0.471 |
| | *Total Recall* | -0.076 | 0.135 | 0.629 | -0.640 |
| | *Aladdin* | -0.331 | 0.328 | 0.082 | -0.090 |
| | *Cinderella* | 0.008 | 0.063 | 0.042 | -0.696 |
| | *Baseball with Comm* | -0.041 | 0.051 | 0.595 | -0.562 |
| | *Snowboard with Comm* | 0.020 | -0.050 | 0.320 | -0.470 |
| | *Oprah w/o Comm* | 0.081 | -0.018 | 0.801 | -0.793 |
| | *Tonight Show w/o Comm* | 0.575 | -0.641 | 0.879 | -0.867 |
| | *Lecture-Gupta* | -0.206 | 0.266 | 0.627 | -0.617 |
| | *Lecture-Reisslein* | 0.188 | -0.502 | 0.579 | -0.831 |
| QCIF | *Jurassic Park I* | 0.240 | -0.193 | 0.537 | -0.422 |
| H.–M.Q. | *Star Wars IV* | 0.114 | -0.209 | 0.458 | -0.460 |
| No R.C. | *The Firm* | 0.351 | -0.323 | 0.806 | -0.748 |
| | *Tonight Show w/o Comm* | 0.353 | -0.330 | 0.750 | -0.689 |
| QCIF | *Citizen Kane* | 0.042 | -0.018 | 0.835 | -0.764 |
| M.Q. | *Die Hard I* | -0.006 | 0.098 | 0.190 | -0.638 |
| No R.C. | *Jurassic Park I* | 0.030 | 0.014 | 0.835 | -0.725 |
| | *Silence of the Lambs* | 0.197 | -0.149 | 0.851 | -0.727 |
| | *Star Wars IV* | 0.016 | 0.012 | 0.583 | -0.674 |
| | *Star Wars V* | 0.065 | -0.069 | 0.832 | -0.710 |
| | *The Firm* | 0.079 | -0.045 | 0.875 | -0.821 |
| | *Terminator I* | 0.027 | -0.005 | 0.601 | -0.686 |
| | *Total Recall* | -0.008 | 0.049 | 0.706 | -0.724 |
| | *Aladdin* | -0.006 | 0.087 | 0.771 | -0.797 |
| | *Cinderella* | 0.001 | 0.074 | 0.294 | -0.779 |
| | *Baseball with Comm* | -0.044 | 0.081 | 0.693 | -0.666 |
| | *Snowboard with Comm* | 0.020 | 0.008 | 0.822 | -0.790 |
| | *Oprah w/o Comm* | -0.138 | 0.189 | 0.893 | -0.850 |
| | *Tonight Show w/o Comm* | 0.148 | -0.211 | 0.912 | -0.783 |
| | *Lecture-Gupta* | -0.356 | 0.458 | 0.925 | -0.834 |
| | *Lecture-Reisslein* | -0.044 | -0.059 | 0.940 | -0.820 |
| QCIF | *Jurassic Park I* | 0.325 | -0.287 | 0.749 | -0.662 |
| M.–L.Q. | *Star Wars IV* | 0.103 | -0.208 | 0.535 | -0.581 |
| No R.C. | *The Firm* | 0.258 | -0.237 | 0.585 | -0.528 |
| | *Tonight Show w/o Comm* | 0.412 | -0.421 | 0.822 | -0.758 |
| QCIF | *Citizen Kane* | 0.224 | -0.210 | 0.550 | -0.474 |
| L.Q. | *Die Hard I* | 0.044 | -0.167 | 0.170 | -0.250 |
| No R.C. | *Jurassic Park I* | 0.214 | -0.172 | 0.423 | -0.326 |
| | *Silence of the Lambs* | 0.317 | -0.270 | 0.551 | -0.452 |
| | *Star Wars IV* | 0.130 | -0.219 | 0.415 | -0.417 |
| | *Star Wars V* | 0.275 | -0.260 | 0.551 | -0.525 |
| | *The Firm* | 0.231 | -0.214 | 0.475 | -0.432 |
| | *Terminator I* | 0.176 | -0.229 | 0.398 | -0.396 |
| | *Total Recall* | 0.200 | -0.197 | 0.328 | -0.320 |
| | *Aladdin* | 0.283 | -0.286 | 0.619 | -0.587 |
| | *Cinderella* | 0.091 | -0.258 | 0.419 | -0.505 |
| | *Baseball with Comm* | 0.175 | -0.172 | 0.308 | -0.303 |
| | *Snowboard with Comm* | 0.194 | -0.198 | 0.415 | -0.418 |
| | *Oprah w/o Comm* | 0.155 | -0.132 | 0.350 | -0.290 |
| | *Tonight Show w/o Comm* | 0.374 | -0.347 | 0.751 | -0.705 |
| | *Lecture-Gupta* | 0.071 | -0.070 | 0.779 | -0.694 |

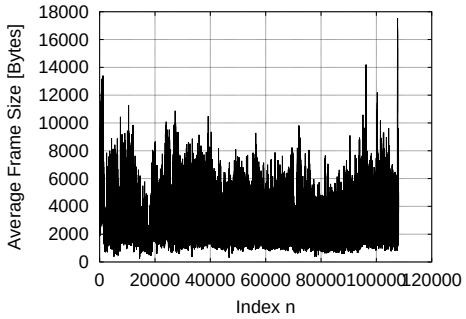
Table 7: *continued*

| Enc. M. | Video | Frame Level $\rho_{XM}$ | Frame Level $\rho_{XQ}$ | GoP level $\rho^{(G)}_{XM}$ | GoP level $\rho^{(G)}_{XQ}$ |
|---|---|---|---|---|---|
| | *Lecture-Reisslein* | 0.259 | -0.264 | 0.888 | -0.829 |
| QCIF | *Citizen Kane* | 0.053 | -0.005 | 0.246 | -0.157 |
| R.C. | *Die Hard I* | 0.045 | -0.163 | 0.166 | -0.235 |
| 64 kbps | *Jurassic Park I* | 0.191 | -0.130 | 0.375 | -0.248 |
| | *Silence of the Lambs* | 0.095 | -0.018 | 0.277 | -0.131 |
| | *Star Wars IV* | 0.072 | -0.079 | 0.262 | -0.248 |
| | *Star Wars V* | 0.193 | -0.145 | 0.411 | -0.367 |
| | *The Firm* | 0.081 | -0.034 | 0.244 | -0.168 |
| | *Terminator I* | 0.156 | -0.191 | 0.359 | -0.356 |
| | *Total Recall* | 0.155 | -0.123 | 0.240 | -0.218 |
| | *Aladdin* | 0.276 | -0.270 | 0.599 | -0.566 |
| | *Cinderella* | 0.092 | -0.251 | 0.414 | -0.490 |
| | *Baseball with Comm* | 0.170 | -0.163 | 0.296 | -0.291 |
| | *Snowboard with Comm* | 0.192 | -0.196 | 0.395 | -0.403 |
| | *Oprah w/o Comm* | 0.131 | -0.089 | 0.289 | -0.223 |
| | *Tonight Show w/o Comm* | 0.076 | -0.030 | 0.299 | -0.167 |
| | *Lecture-Gupta* | 0.079 | -0.077 | 0.764 | -0.685 |
| | *Lecture-Reisslein* | 0.211 | -0.205 | 0.827 | -0.738 |
| QCIF | *Citizen Kane* | -0.042 | 0.087 | -0.027 | 0.024 |
| R.C. | *Die Hard I* | -0.018 | 0.126 | -0.002 | 0.053 |
| 128 kbps | *Jurassic Park I* | -0.035 | 0.066 | 0.141 | -0.039 |
| | *Silence of the Lambs* | -0.021 | 0.079 | 0.169 | -0.037 |
| | *Star Wars IV* | -0.033 | 0.113 | -0.005 | 0.032 |
| | *Star Wars V* | -0.062 | 0.084 | -0.020 | 0.024 |
| | *The Firm* | -0.050 | 0.088 | -0.008 | 0.018 |
| | *Terminator I* | -0.028 | 0.083 | 0.104 | -0.042 |
| | *Total Recall* | -0.066 | 0.105 | -0.036 | 0.035 |
| | *Aladdin* | -0.013 | 0.074 | 0.162 | -0.089 |
| | *Cinderella* | -0.018 | 0.120 | 0.111 | -0.026 |
| | *Baseball with Comm* | -0.081 | 0.122 | -0.009 | 0.018 |
| | *Snowboard with Comm* | -0.040 | 0.082 | 0.076 | -0.040 |
| | *Oprah w/o Comm* | -0.079 | 0.103 | -0.012 | 0.024 |
| | *Tonight Show w/o Comm* | -0.044 | 0.019 | 0.025 | 0.001 |
| | *Lecture-Gupta* | -0.184 | 0.292 | 0.038 | -0.014 |
| | *Lecture-Reisslein* | -0.122 | 0.082 | 0.042 | -0.030 |
| QCIF | *Citizen Kane* | -0.112 | 0.178 | -0.047 | 0.051 |
| R.C. | *Die Hard I* | -0.027 | 0.291 | -0.009 | 0.082 |
| 256 kbps | *Jurassic Park I* | -0.117 | 0.172 | -0.030 | 0.042 |
| | *Silence of the Lambs* | -0.085 | 0.193 | -0.026 | 0.049 |
| | *Star Wars IV* | -0.122 | 0.222 | -0.031 | 0.060 |
| | *Star Wars V* | -0.171 | 0.176 | -0.071 | 0.054 |
| | *The Firm* | -0.131 | 0.204 | -0.041 | 0.049 |
| | *Terminator I* | -0.171 | 0.229 | -0.045 | 0.064 |
| | *Total Recall* | -0.192 | 0.262 | -0.075 | 0.073 |
| | *Aladdin* | -0.178 | 0.265 | -0.086 | 0.076 |
| | *Cinderella* | -0.037 | 0.246 | 0.062 | 0.023 |
| | *Baseball with Comm* | -0.219 | 0.273 | -0.084 | 0.071 |
| | *Snowboard with Comm* | -0.191 | 0.221 | -0.058 | 0.055 |
| | *Oprah w/o Comm* | -0.188 | 0.214 | -0.070 | 0.064 |
| | *Tonight Show w/o Comm* | -0.114 | 0.044 | -0.051 | 0.014 |
| | *Lecture-Gupta* | -0.331 | 0.430 | -0.074 | 0.076 |
| | *Lecture-Reisslein* | -0.267 | 0.158 | -0.033 | 0.018 |
| CIF | *Silence of the Lambs* | 0.435 | -0.363 | 0.765 | -0.669 |
| 040404. | *Terminator I* | 0.209 | -0.351 | 0.644 | -0.669 |
| No.R.C. | *Snowboard with Comm* | 0.144 | -0.137 | 0.516 | -0.445 |
| | *Oprah w/o Comm* | 0.251 | -0.199 | 0.887 | -0.877 |
| | *ParkingLot* | -0.407 | 0.417 | 0.144 | -0.135 |
| | *LectureHQ-Reisslein* | -0.278 | 0.354 | 0.790 | -0.782 |
| CIF | *Silence of the Lambs* | 0.093 | 0.055 | 0.853 | -0.793 |
| 040608. | *Terminator I* | -0.002 | 0.13 | 0.661 | -0.781 |

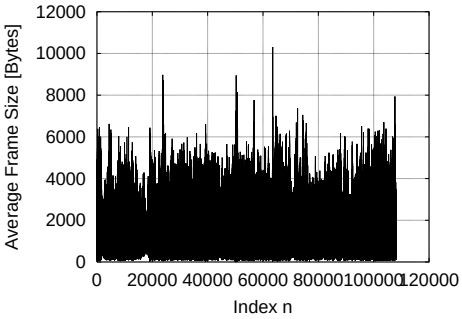
Table 7: *continued*

| Enc. M. | Video | Frame Level $\rho_{XM}$ | Frame Level $\rho_{XQ}$ | GoP level $\rho^{(G)}_{XM}$ | GoP level $\rho^{(G)}_{XQ}$ |
|---|---|---|---|---|---|
| No.R.C. | *Snowboard with Comm* | -0.318 | 0.436 | 0.761 | -0.720 |
| | *Oprah w/o Comm* | -0.472 | 0.6 | 0.899 | -0.905 |
| | *ParkingLot* | -0.485 | 0.655 | 0.879 | -0.830 |
| | *LectureHQ-Reisslein* | -0.618 | 0.745 | 0.847 | -0.840 |
| CIF | *Silence of the Lambs* | 0.348 | -0.272 | 0.849 | -0.775 |
| 060810. | *Terminator I* | 0.081 | -0.14 | 0.492 | -0.758 |
| No.R.C. | *Snowboard with Comm* | -0.062 | 0.132 | 0.765 | -0.734 |
| | *Oprah w/o Comm* | -0.292 | 0.358 | 0.876 | -0.864 |
| | *ParkingLot* | -0.204 | 0.365 | 0.637 | -0.614 |
| | *LectureHQ-Reisslein* | -0.435 | 0.535 | 0.809 | -0.793 |
| CIF | *Silence of the Lambs* | 0.61 | -0.532 | 0.777 | -0.689 |
| 101010. | *Terminator I* | 0.153 | -0.47 | 0.415 | -0.671 |
| No.R.C. | *Snowboard with Comm* | 0.384 | -0.402 | 0.709 | -0.676 |
| | *Oprah w/o Comm* | 0.307 | -0.293 | 0.825 | -0.785 |
| | *ParkingLot* | 0.107 | -0.053 | 0.645 | -0.582 |
| | *LectureHQ-Reisslein* | -0.060 | 0.083 | 0.625 | -0.603 |
| CIF | *Silence of the Lambs* | 0.436 | -0.365 | 0.829 | -0.738 |
| 101416. | *Terminator I* | 0.11 | -0.255 | 0.462 | -0.695 |
| No.R.C. | *Snowboard with Comm* | 0.109 | -0.073 | 0.754 | -0.712 |
| | *Oprah w/o Comm* | -0.096 | 0.13 | 0.843 | -0.817 |
| | *ParkingLot* | -0.031 | 0.166 | 0.914 | -0.904 |
| | *LectureHQ-Reisslein* | -0.255 | 0.308 | 0.753 | -0.722 |
| CIF | *Silence of the Lambs* | 0.552 | -0.468 | 0.69 | -0.608 |
| 242424. | *Terminator I* | 0.251 | -0.433 | 0.486 | -0.549 |
| No.R.C. | *Snowboard with Comm* | 0.362 | -0.335 | 0.574 | -0.527 |
| | *Oprah w/o Comm* | 0.308 | -0.287 | 0.563 | -0.532 |
| | *ParkingLot* | 0.245 | -0.197 | 0.575 | -0.474 |
| | *LectureHQ-Reisslein* | 0.028 | -0.018 | 0.304 | -0.274 |
| CIF | *Silence of the Lambs* | 0.528 | -0.456 | 0.65 | -0.585 |
| 303030. | *Terminator I* | 0.304 | -0.433 | 0.5 | -0.531 |
| No.R.C. | *Snowboard with Comm* | 0.351 | -0.317 | 0.515 | -0.472 |
| | *Oprah w/o Comm* | 0.312 | -0.285 | 0.451 | -0.422 |
| | *ParkingLot* | 0.259 | -0.204 | 0.518 | -0.406 |
| | *LectureHQ-Reisslein* | 0.059 | -0.047 | 0.203 | -0.173 |
| CIF | *Silence of the Lambs* | 0.527 | -0.455 | 0.646 | -0.583 |
| 64kbps | *Terminator I* | 0.307 | -0.435 | 0.499 | -0.529 |
| R.C. | *Snowboard with Comm* | 0.349 | -0.316 | 0.504 | -0.462 |
| | *Oprah w/o Comm* | 0.315 | -0.287 | 0.435 | -0.405 |
| | *ParkingLot* | 0.264 | -0.209 | 0.502 | -0.393 |
| | *LectureHQ-Reisslein* | 0.068 | -0.055 | 0.194 | -0.165 |
| CIF | *Silence of the Lambs* | 0.527 | -0.455 | 0.647 | -0.584 |
| 128kbps | *Terminator I* | 0.307 | -0.434 | 0.498 | -0.527 |
| R.C. | *Snowboard with Comm* | 0.349 | -0.316 | 0.504 | -0.462 |
| | *Oprah w/o Comm* | 0.315 | -0.287 | 0.435 | -0.405 |
| | *ParkingLot* | 0.264 | -0.209 | 0.502 | -0.392 |
| | *LectureHQ-Reisslein* | 0.068 | -0.055 | 0.194 | -0.164 |
| CIF | *Silence of the Lambs* | 0.274 | -0.14 | 0.48 | -0.317 |
| 256kbps | *Terminator I* | 0.304 | -0.421 | 0.494 | -0.511 |
| R.C. | *Snowboard with Comm* | 0.339 | -0.305 | 0.502 | -0.461 |
| | *Oprah w/o Comm* | 0.212 | -0.167 | 0.398 | -0.360 |
| | *ParkingLot* | 0.262 | -0.205 | 0.501 | -0.390 |
| | *LectureHQ-Reisslein* | -0.103 | 0.159 | -0.046 | 0.074 |
| CIF | *ParkingLot* | -0.081 | 0.195 | -0.005 | 0.095 |
| 512kbps | *LectureHQ-Reisslein* | -0.167 | 0.239 | -0.049 | 0.055 |
| R.C. | *Silence of the Lambs* | | | | |
| CIF | *ParkingLot* | -0.197 | 0.259 | -0.093 | 0.105 |
| 1024kbps | *LectureHQ-Reisslein* | -0.285 | 0.390 | -0.092 | 0.095 |
| R.C. | *Silence of the Lambs* | | | | |

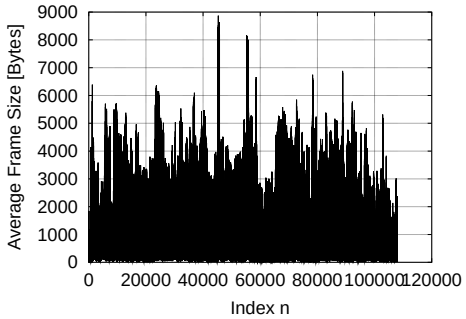
Figure 19 gives rate-distortion plots, i.e., the average video quality $\bar{Q}$ as a function of the mean bit rate. The plots are obtained from the five different quality level encodings of four different videos.



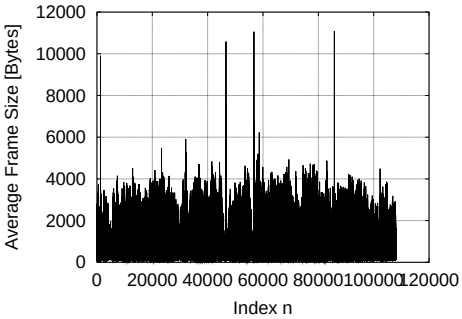

a) *Star Wars IV* with high quality



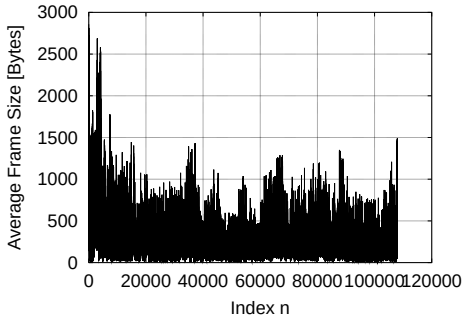

d) *Star Wars IV* with 256 kbps target bit rate



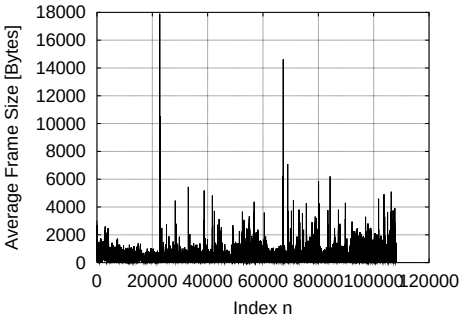

b) *Jurassic Park I* with medium quality




e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

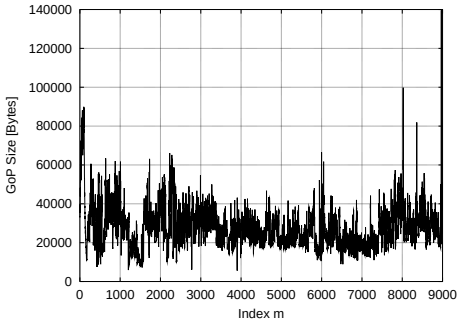



f) *Silence of the Lambs* with 64 kbps target bit rate

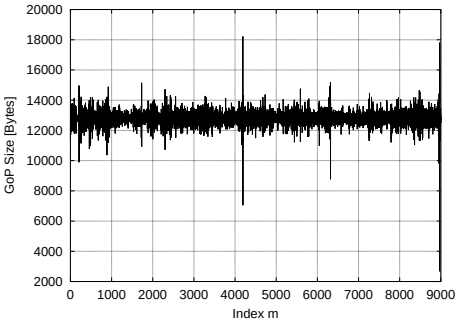
Encoding without rate control

Encoding with rate control

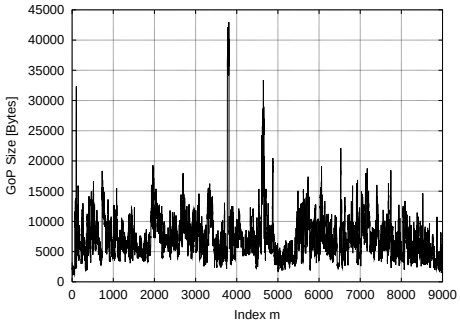
Figure 1: Frame size $X_n$ as a function of the frame index $n$ for single-layer QCIF video.



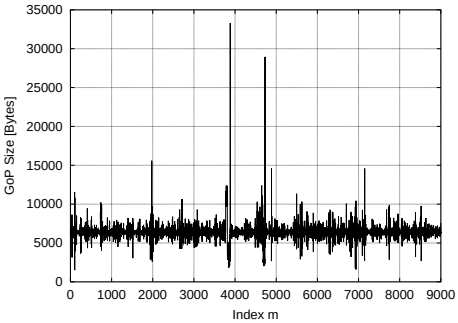

a) *Star Wars IV* with high quality



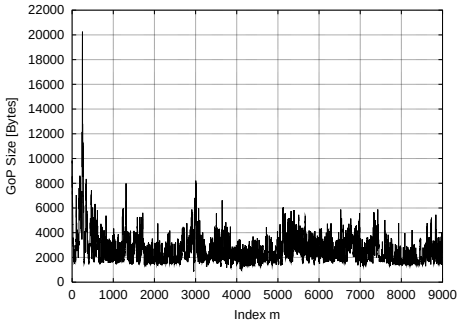

d) *Star Wars IV* with 256 kbps target bit rate



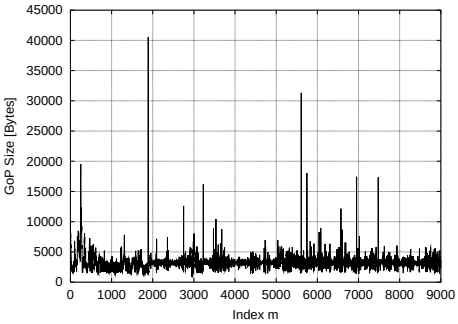

b) *Jurassic Park I* with medium quality




e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

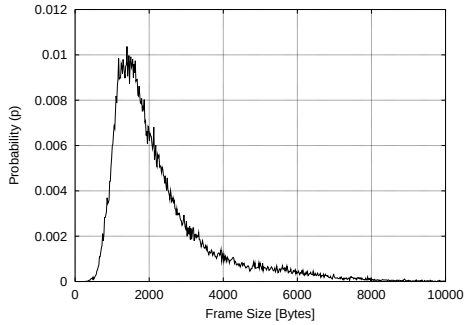



f) *Silence of the Lambs* with 64 kbps target bit rate

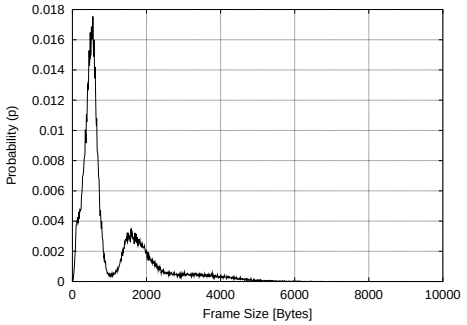
Encoding without rate control

Encoding with rate control

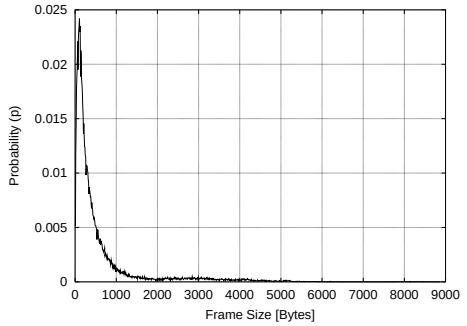
Figure 2: GoP size $Y_m$ as a function of the index $m$ for single-layer QCIF video.



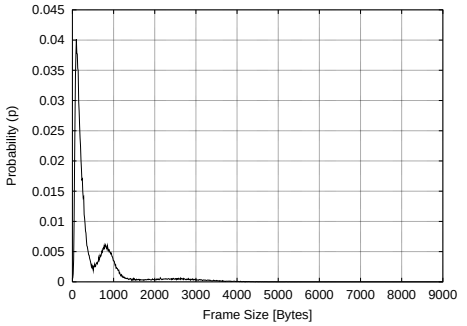

a) *Star Wars IV* with high quality



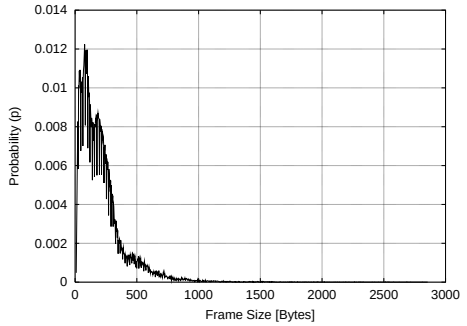

d) *Star Wars IV* with 256 kbps target bit rate



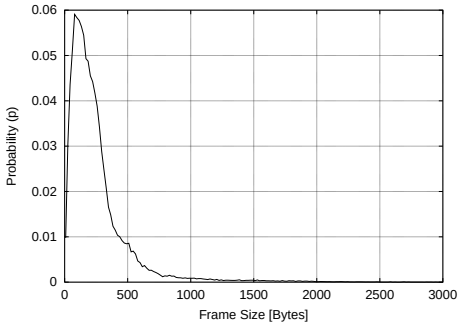

b) *Jurassic Park I* with medium quality




e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

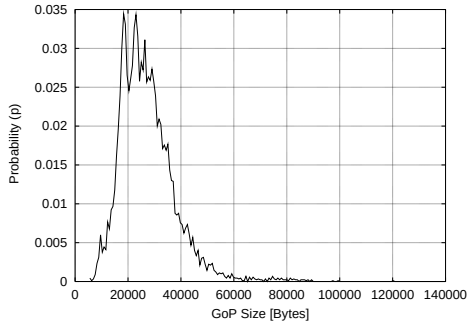



f) *Silence of the Lambs* with 64 kbps target bit rate

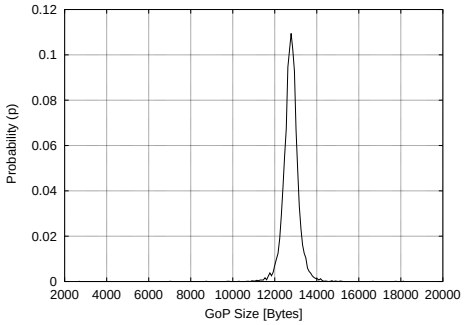
Encoding without rate control

Encoding with rate control

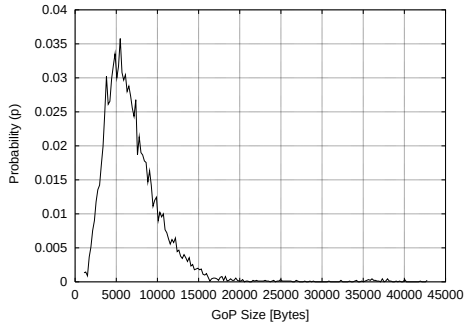
Figure 3: Frame size histograms for single-layer QCIF video.



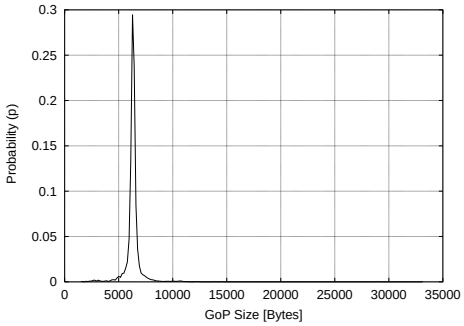

a) *Star Wars IV* with high quality



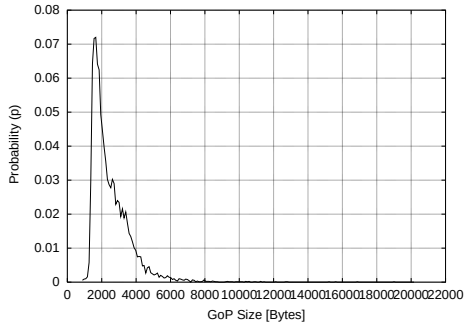

d) *Star Wars IV* with 256 kbps target bit rate




b) *Jurassic Park I* with medium quality

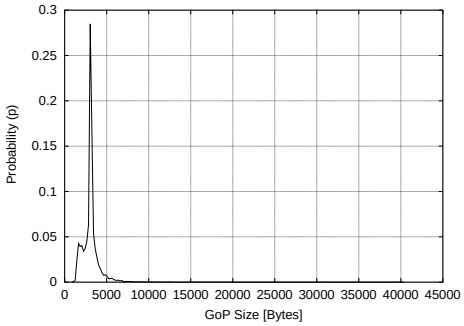



e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

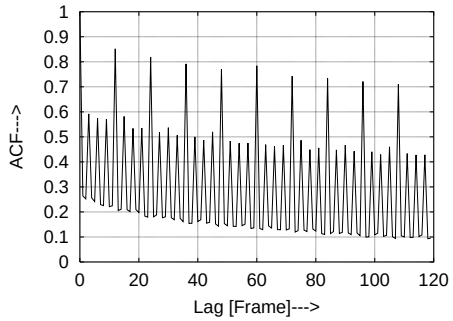
Encoding without rate control



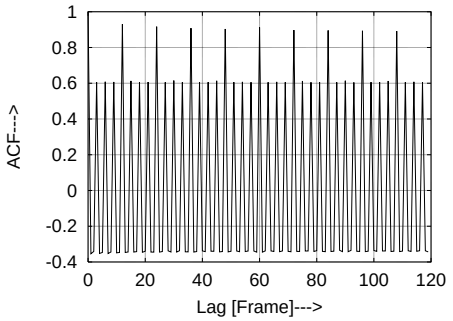

f) *Silence of the Lambs* with 64 kbps target bit rate

Encoding with rate control

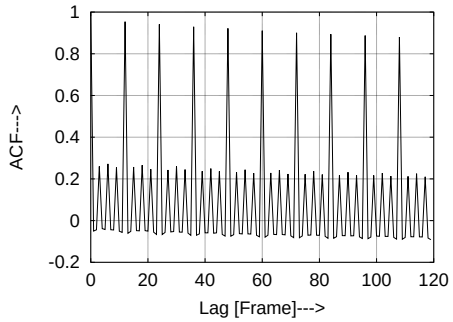
Figure 4: GoP size histograms for single-layer QCIF video.



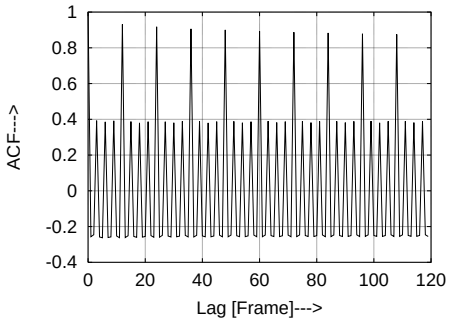

a) *Star Wars IV* with high quality



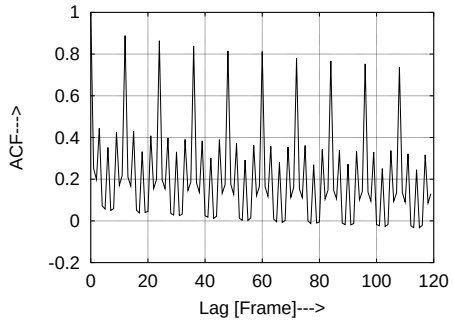

d) *Star Wars IV* with 256 kbps target bit rate



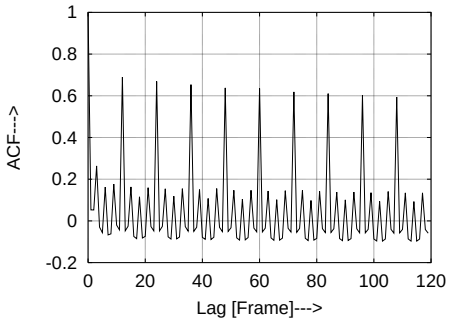

b) *Jurassic Park I* with medium quality




e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

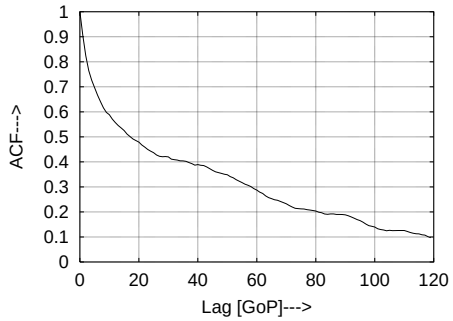



f) *Silence of the Lambs* with 64 kbps target bit rate

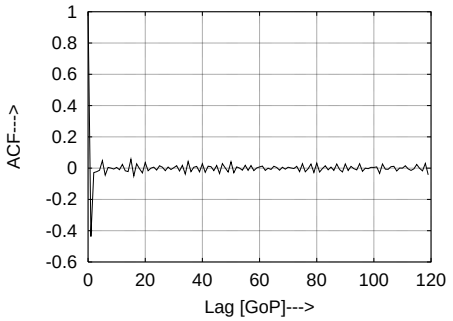
Encoding without rate control

Encoding with rate control

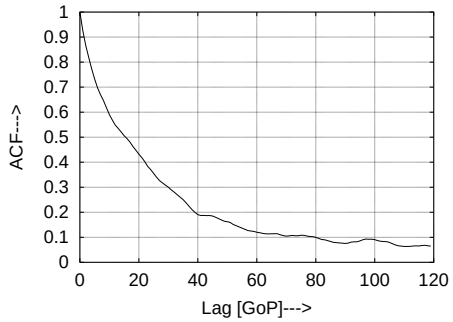
Figure 5: Frame size autocorrelations for single-layer QCIF video.



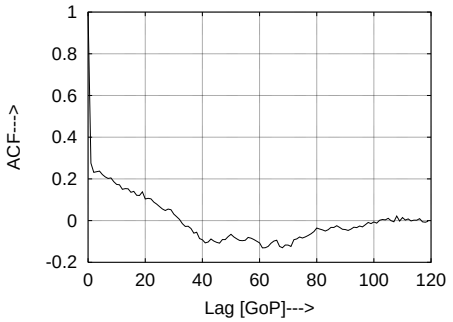

a) *Star Wars IV* with high quality



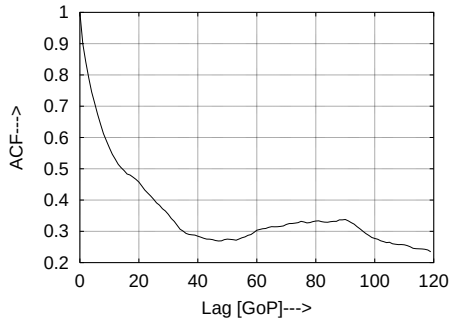

d) *Star Wars IV* with 256 kbps target bit rate



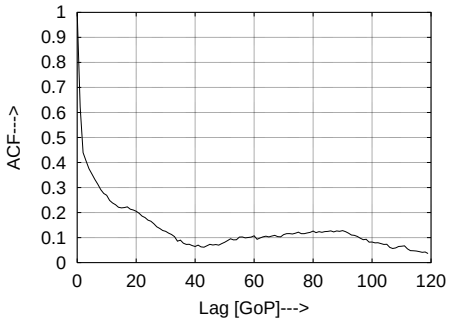

b) *Jurassic Park I* with medium quality




e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

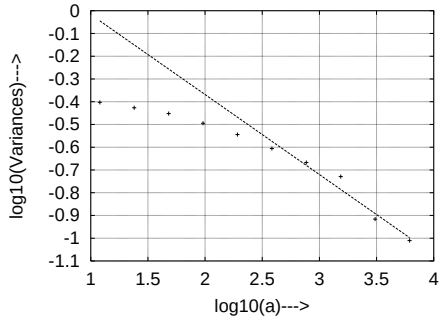



f) *Silence of the Lambs* with 64 kbps target bit rate

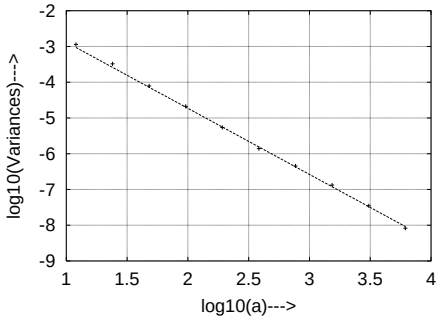
Encoding without rate control

Encoding with rate control

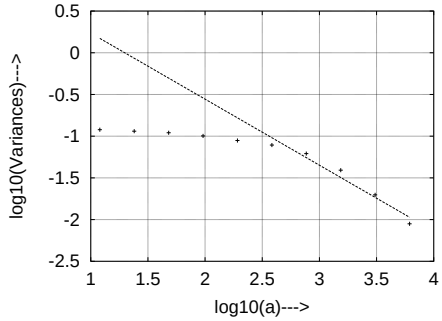
Figure 6: GoP size autocorrelations for single-layer QCIF video.



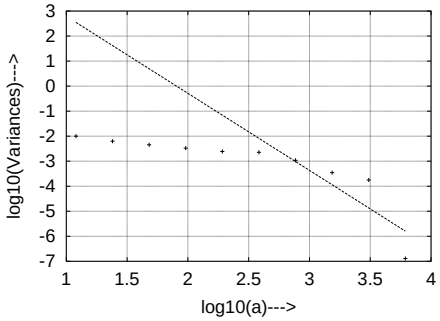

a) *Star Wars IV* with high quality, H=0.824



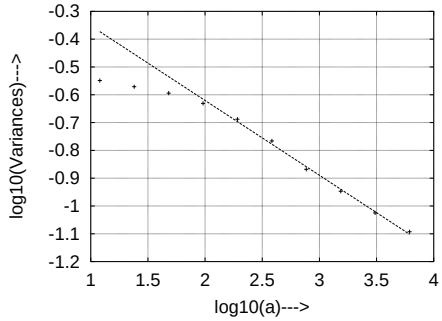

d) *Star Wars IV* with 256 kbps target bit rate, H=0.075



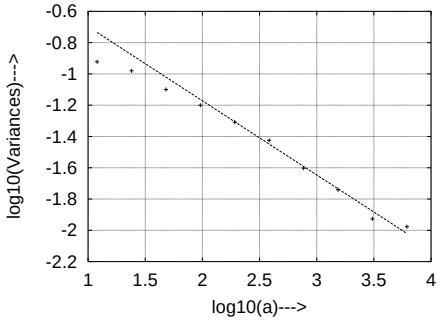

b) *Jurassic Park I* with medium quality, H=0.604




e) *Jurassic Park I* with 128 kbps target bit rate, H=0.539




c) *Silence of the Lambs* with low quality, H=0.865

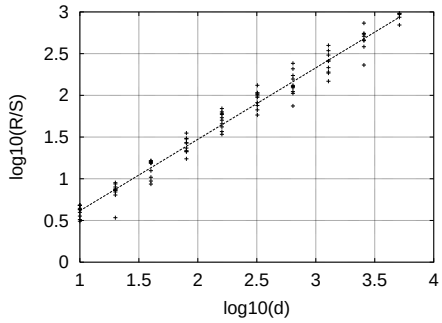



f) *Silence of the Lambs* with 64 kbps target bit rate, H=0.763

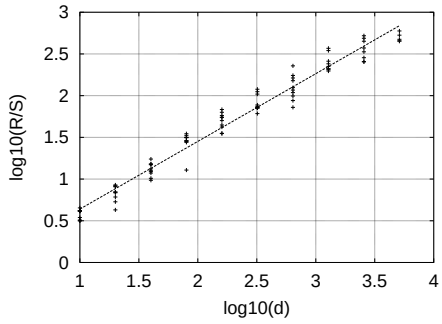
Encoding without rate control

Encoding with rate control

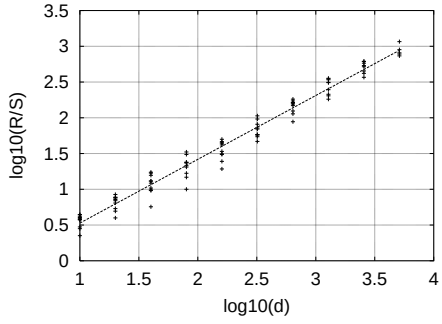
Figure 7: Variance time plots for single-layer QCIF video.




a) *Star Wars IV* with high quality, H=0.856

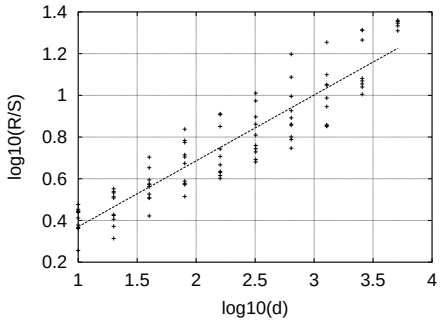



b) *Jurassic Park I* with medium quality, H=0.811

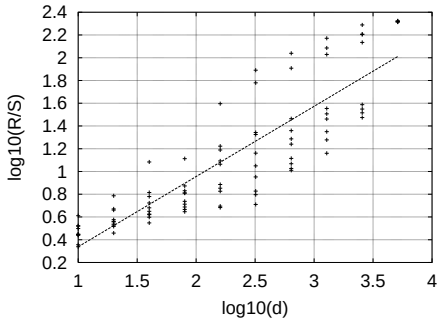



c) *Silence of the Lambs* with low quality, H=0.892

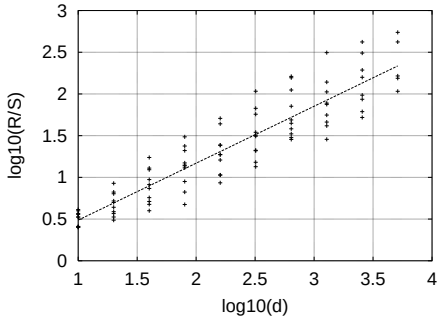
Encoding without rate control




d) *Star Wars IV* with 256 kbps target bit rate, H=0.657



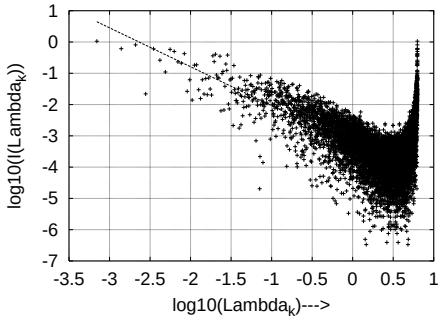

e) *Jurassic Park I* with 128 kbps target bit rate, H=0.385



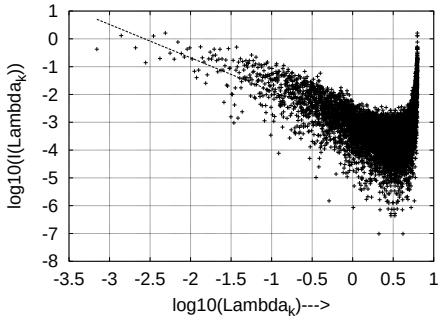

f) *Silence of the Lambs* with 64 kbps target bit rate, H=0.316

Encoding with rate control

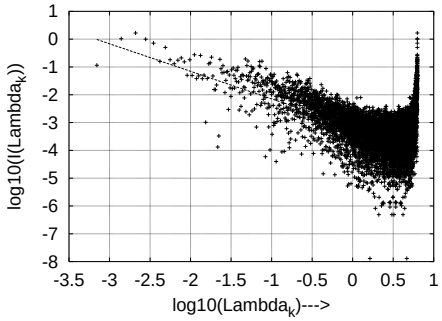
Figure 8: Pox plots of R/S for aggregation level $a = 12$ for single-layer QCIF video.




a) *Star Wars IV* with high quality, H=1.122

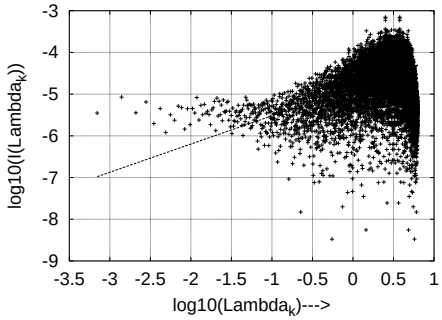



b) *Jurassic Park I* with medium quality, H=1.098

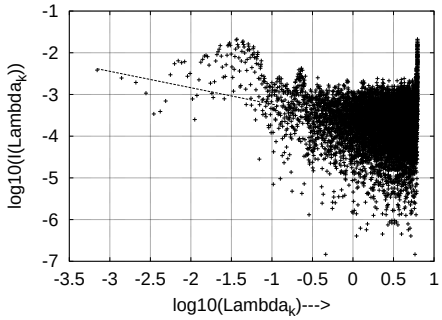



c) *Silence of the Lambs* with low quality, H=0.995

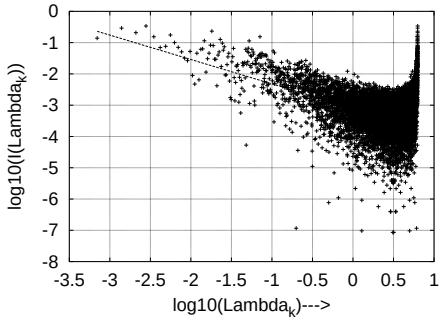
Encoding without rate control




d) *Star Wars IV* with 256 kbps target bit rate, H=0.162



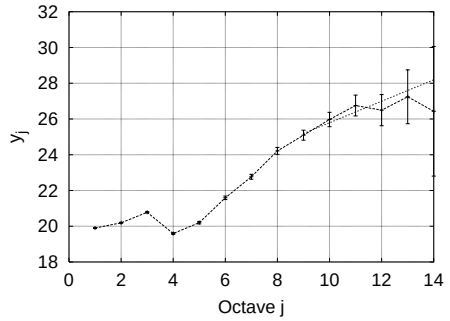

e) *Jurassic Park I* with 128 kbps target bit rate, H=0.696



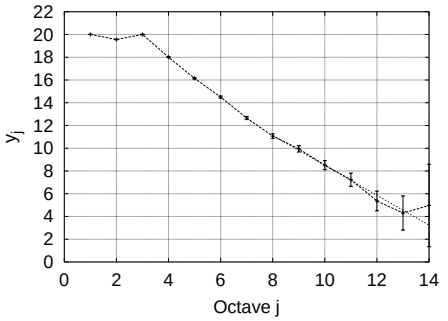

f) *Silence of the Lambs* with 64 kbps target bit rate, H=0.889

Encoding with rate control

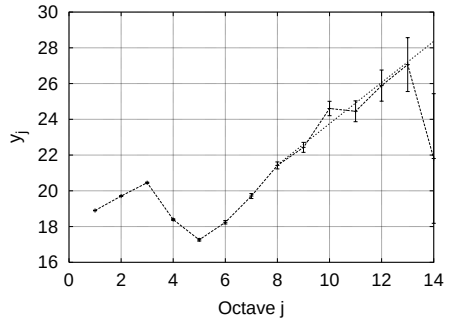
Figure 9: Periodogram for aggregation level $a = 12$ for single-layer QCIF video.



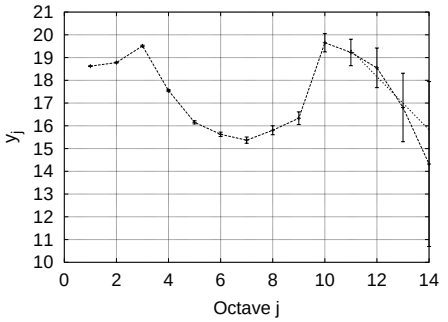

a) *Star Wars IV* with high quality



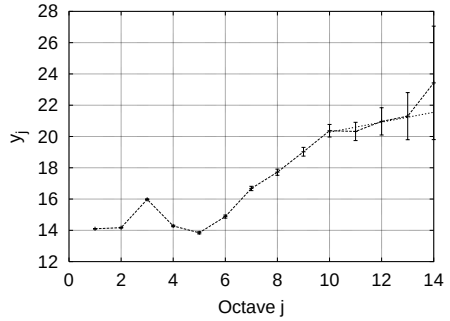

d) *Star Wars IV* with 256 kbps target bit rate



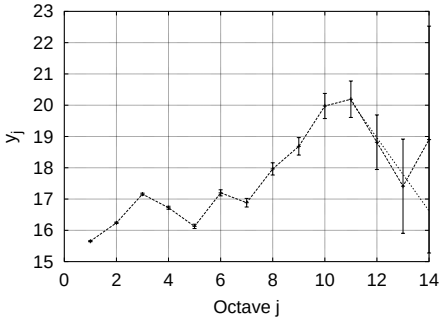

b) *Jurassic Park I* with medium quality




e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

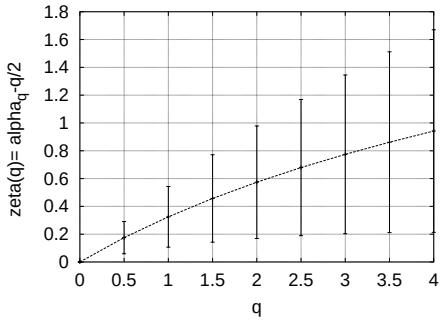



f) *Silence of the Lambs* with 64 kbps target bit rate

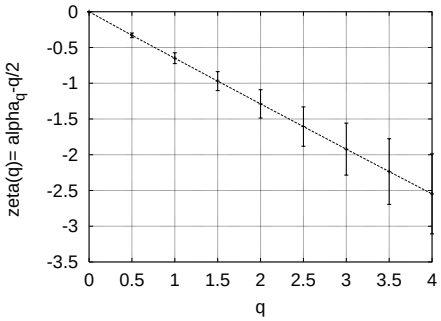
Encoding without rate control

Encoding with rate control

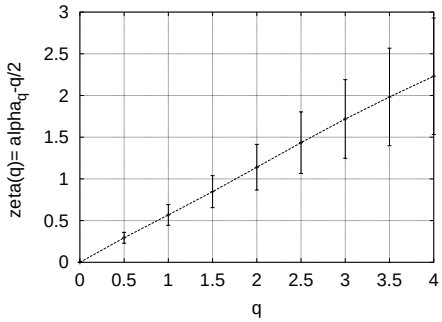
Figure 10: Logscale diagrams for single-layer QCIF video.



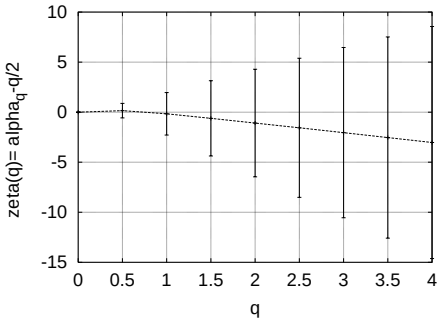

a) *Star Wars IV* with high quality



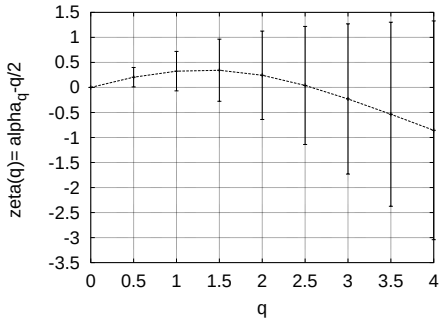

d) *Star Wars IV* with 256 kbps target bit rate



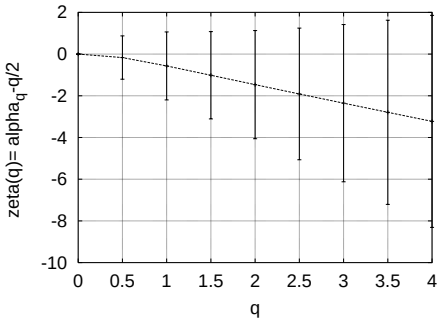

b) *Jurassic Park I* with medium quality




e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

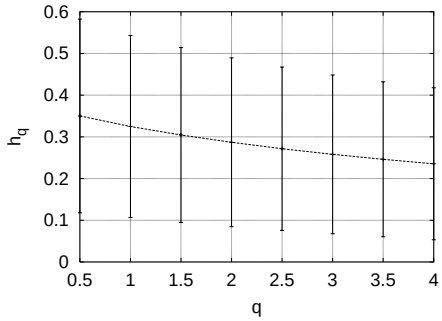



f) *Silence of the Lambs* with 64 kbps target bit rate

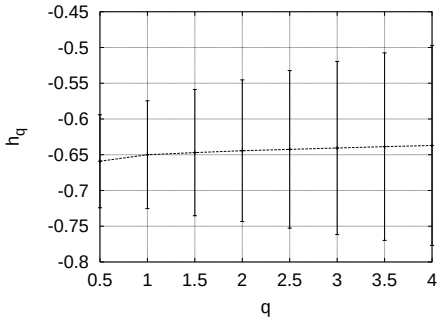
Encoding without rate control

Encoding with rate control

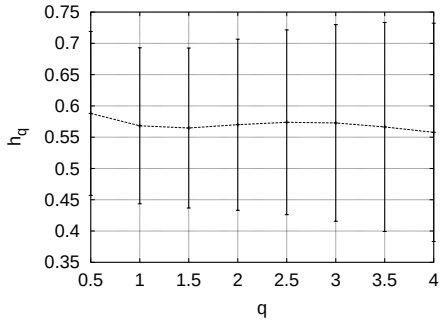
Figure 11: Multiscale diagrams for single-layer QCIF video.



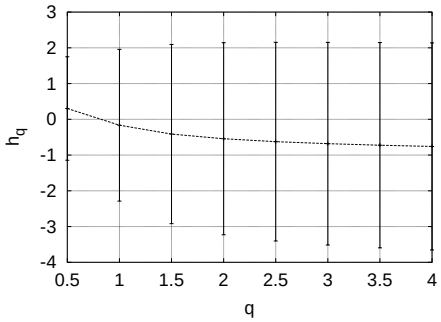

a) *Star Wars IV* with high quality



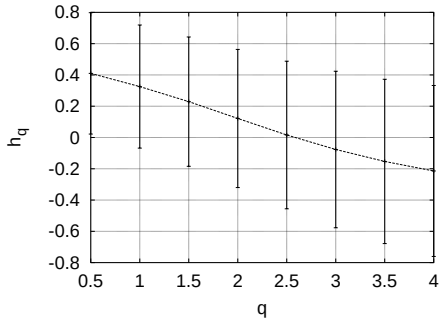

d) *Star Wars IV* with 256 kbps target bit rate



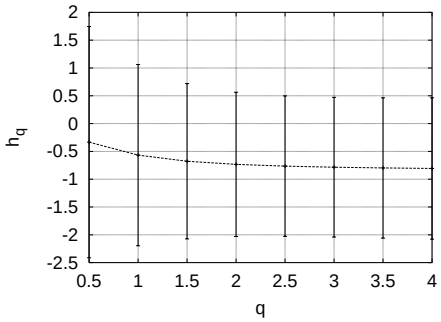

b) *Jurassic Park I* with medium quality




e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

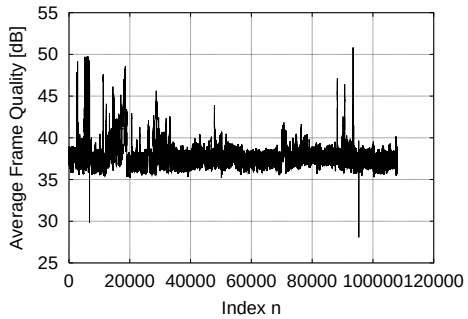



f) *Silence of the Lambs* with 64 kbps target bit rate

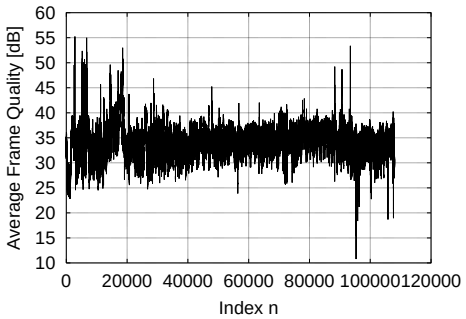
Encoding without rate control

Encoding with rate control

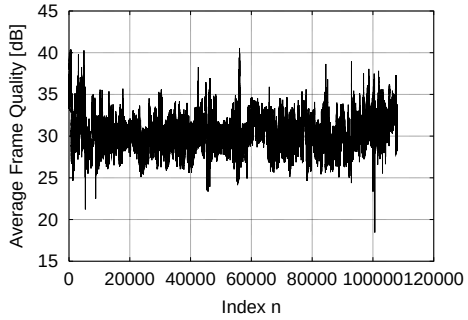
Figure 12: Linear multiscale diagrams for single-layer QCIF video.



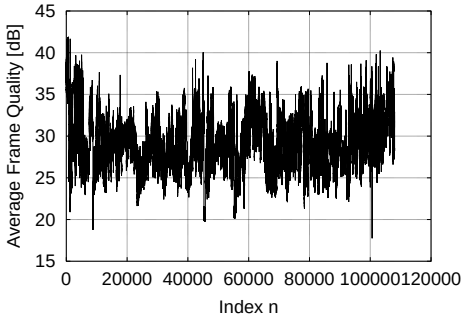

a) *Star Wars IV* with high quality



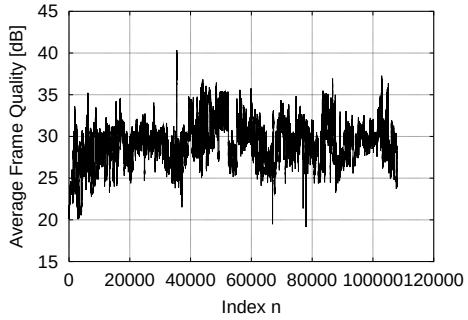

d) *Star Wars IV* with 256 kbps target bit rate



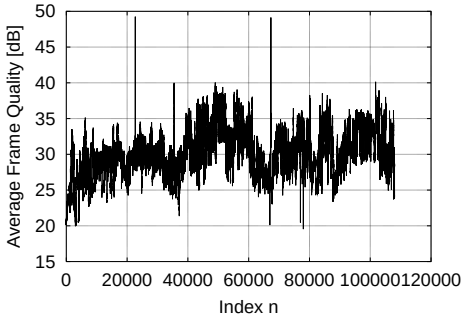

b) *Jurassic Park I* with medium quality




e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

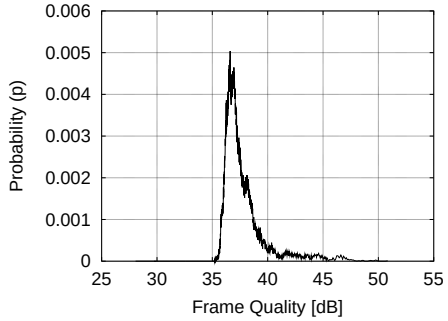



f) *Silence of the Lambs* with 64 kbps target bit rate

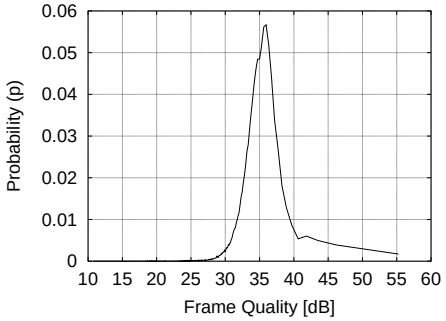
Encoding without rate control

Encoding with rate control

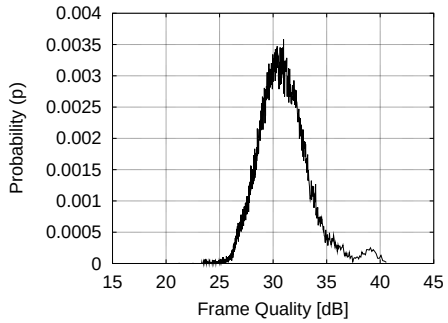
Figure 13: Video frame quality $Q_n$ (in dB) as a function of the frame index $n$ for single-layer QCIF video.



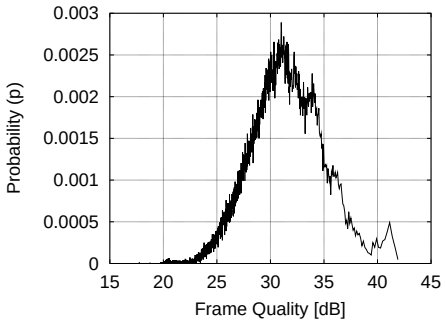

a) *Star Wars IV* with high quality



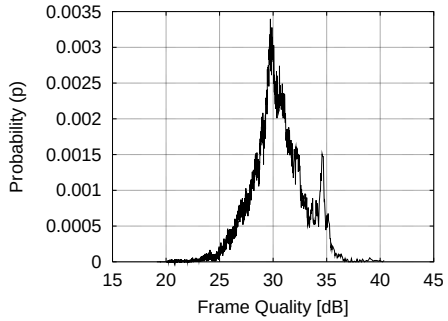

d) *Star Wars IV* with 256 kbps target bit rate



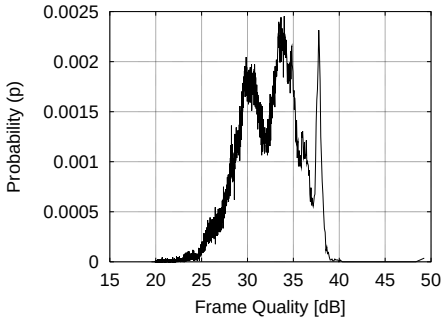

b) *Jurassic Park I* with medium quality




e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

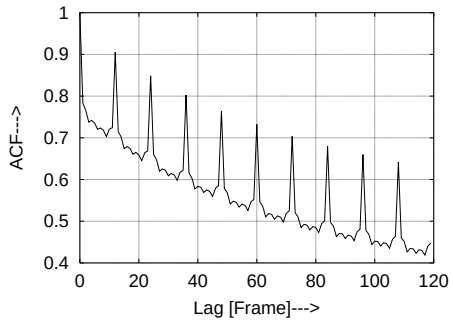



f) *Silence of the Lambs* with 64 kbps target bit rate

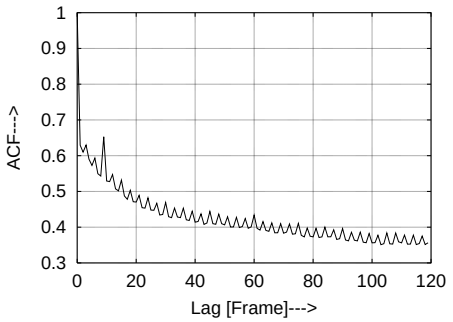
Encoding without rate control

Encoding with rate control

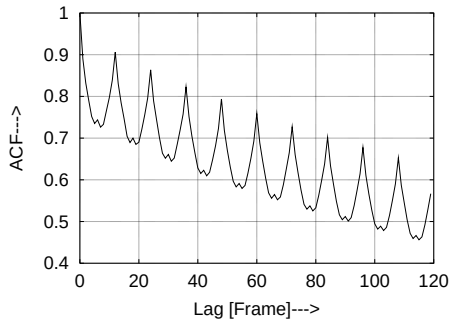
Figure 14: Histograms of video frame quality $Q_n$ (in dB) of single-layer QCIF video.



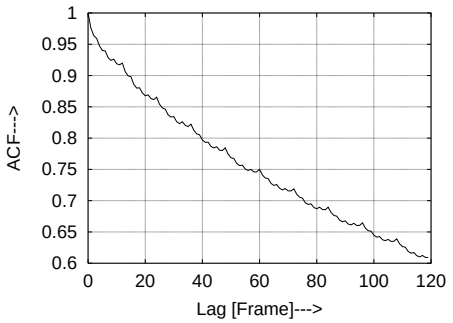

a) *Star Wars IV* with high quality



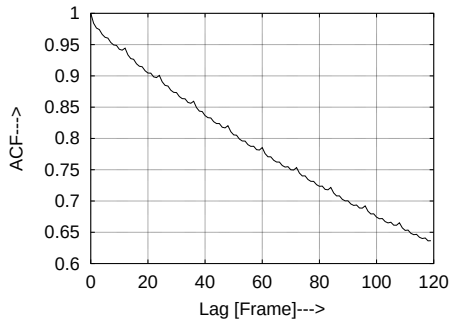

d) *Star Wars IV* with 256 kbps target bit rate



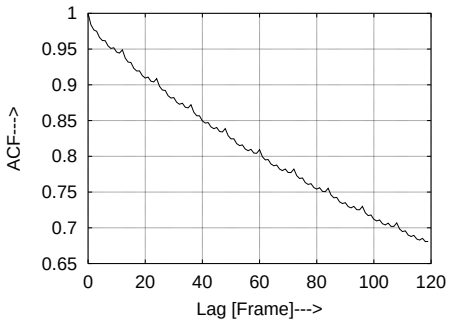

b) *Jurassic Park I* with medium quality




e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

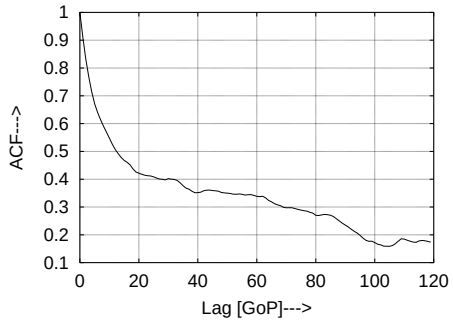



f) *Silence of the Lambs* with 64 kbps target bit rate

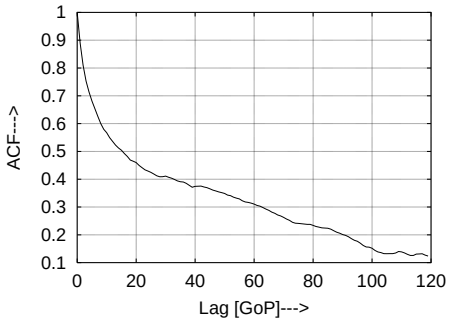
Encoding without rate control

Encoding with rate control

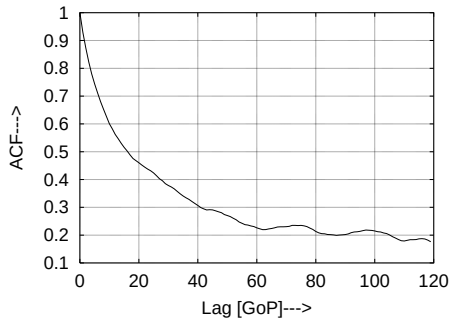
Figure 15: MSE autocorrelation coefficient $\rho_M(k)$ as as function of the lag $k$ (in frames) for single-layer QCIF video.



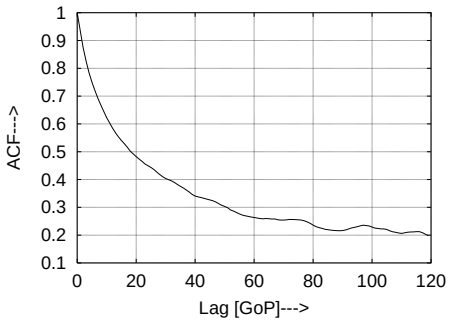

a) *Star Wars IV* with high quality



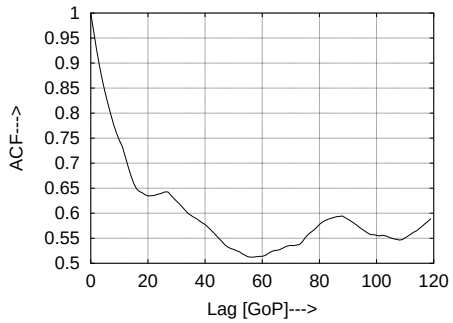

d) *Star Wars IV* with 256 kbps target bit rate



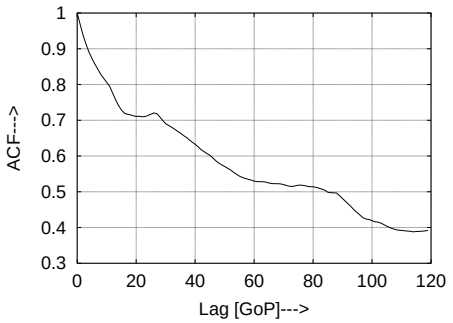

b) *Jurassic Park I* with medium quality




e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

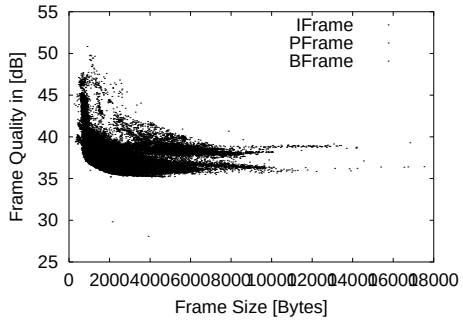



f) *Silence of the Lambs* with 64 kbps target bit rate

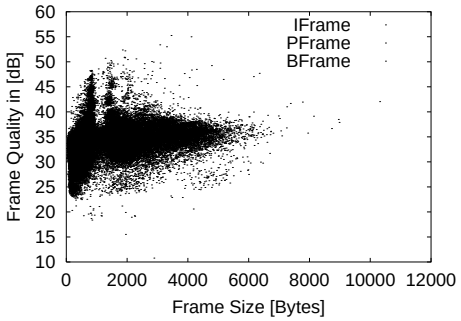
Encoding without rate control

Encoding with rate control

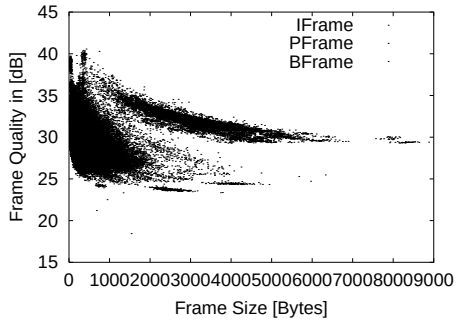
Figure 16: MSE autocorrelation coefficient $\rho_M^{(G)}(k)$ as a function of the lag $k$ (in GoPs) for single-layer QCIF video.



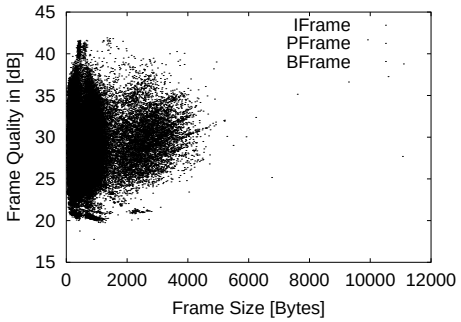

a) *Star Wars IV* with high quality



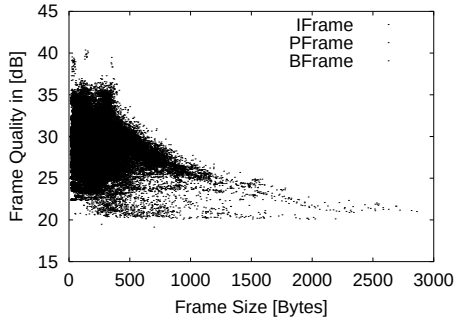

d) *Star Wars IV* with 256 kbps target bit rate



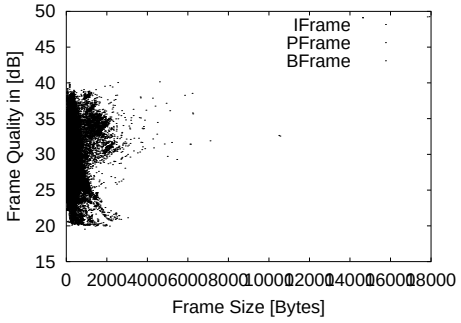

b) *Jurassic Park I* with medium quality




e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

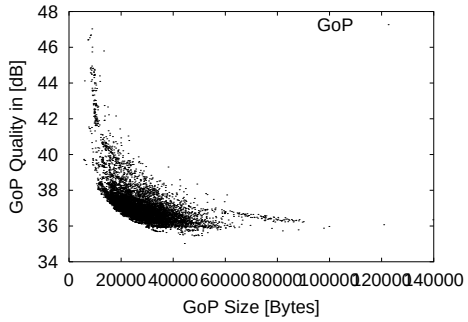



f) *Silence of the Lambs* with 64 kbps target bit rate

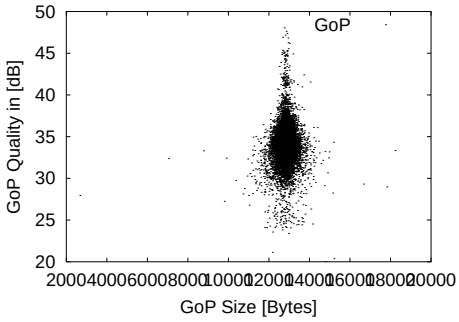
Encoding without rate control

Encoding with rate control

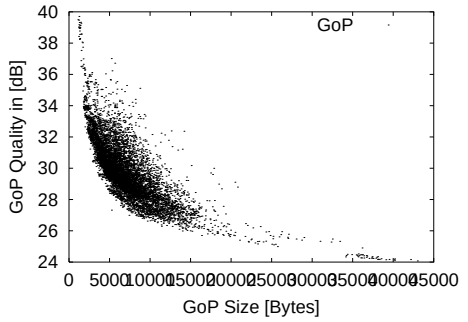
Figure 17: Scatter plots of frame size and frame quality for single-layer QCIF video.



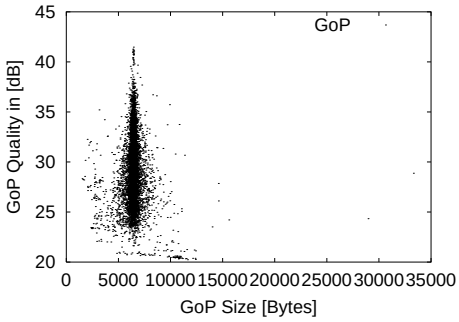

a) *Star Wars IV* with high quality



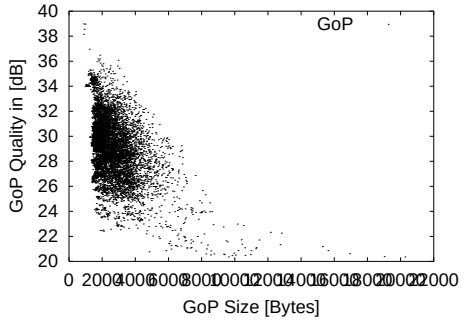

d) *Star Wars IV* with 256 kbps target bit rate




b) *Jurassic Park I* with medium quality

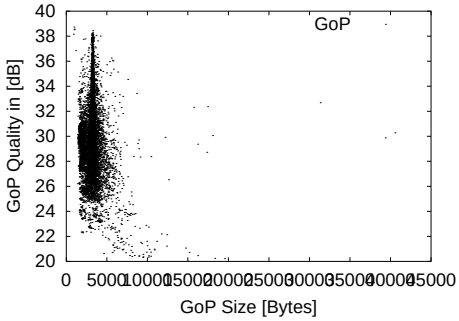



e) *Jurassic Park I* with 128 kbps target bit rate




c) *Silence of the Lambs* with low quality

Encoding without rate control




f) *Silence of the Lambs* with 64 kbps target bit rate

Encoding with rate control

Figure 18: Scatter plots of GoP size and average GoP quality for single-layer QCIF video.

Table 8: Overview of Motion Vector Statistics of single-layer traces

| Format | Sequence | $\tilde{X}_M^P$ | $\tilde{X}_T^P$ | $\tilde{MB}_{Inter}$ | $\tilde{MB}_{Intra}$ | $\tilde{N}_{Intra}$ | $CoQV$ |
|---|---|---|---|---|---|---|---|
| CIF | *Silence of the Lambs* | | | | | | |
| 040404. | *Terminator I* | 9.044 | 90.859 | 352 | 29 | 4425 | 0.006 |
| No.R.C. | *Snowboard with Comm* | 6.289 | 93.657 | 359 | 32 | 4403 | 0.003 |
| | *Oprah w/o Comm* | 4.239 | 95.719 | 362 | 18 | 1595 | 0.001 |
| | *ParkingLot* | 2.098 | 97.856 | 362 | 3 | 1263 | 0 |
| | *LectureHQ-Reisslein* | 6.967 | 92.9 | 354 | 13 | 203 | 0.002 |
| CIF | *Silence of the Lambs* | 31.172 | 68.291 | 297 | 22 | 1545 | 0.045 |
| 040608. | *Terminator I* | 20.291 | 79.444 | 317 | 29 | 4458 | 0.023 |
| No.R.C. | *Snowboard with Comm* | 17.386 | 82.449 | 351 | 32 | 4391 | 0.022 |
| | *Oprah w/o Comm* | 13.235 | 86.615 | 357 | 19 | 1572 | 0.006 |
| | *ParkingLot* | 5.703 | 94.124 | 338 | 3 | 1275 | 0.002 |
| | *LectureHQ-Reisslein* | 19.581 | 79.873 | 241 | 14 | 201 | 0.018 |
| CIF | *Silence of the Lambs* | 35.357 | 63.689 | 244 | 22 | 1565 | 0.043 |
| 060810. | *Terminator I* | 24.709 | 74.907 | 291 | 29 | 4470 | 0.027 |
| No.R.C. | *Snowboard with Comm* | 22.605 | 77.148 | 329 | 32 | 4408 | 0.028 |
| | *Oprah w/o Comm* | 20.411 | 79.348 | 347 | 18 | 1570 | 0.012 |
| | *ParkingLot* | 8.456 | 91.268 | 308 | 3 | 1308 | 0.003 |
| | *LectureHQ-Reisslein* | 21.679 | 77.371 | 174 | 13 | 209 | 0.024 |
| CIF | *Silence of the Lambs* | | | | | | |
| 101010. | *Terminator I* | 25.106 | 74.512 | 286 | 29 | 4514 | 0.025 |
| No.R.C. | *Snowboard with Comm* | 20.878 | 78.85 | 305 | 32 | 4391 | 0.022 |
| | *Oprah w/o Comm* | 21.153 | 78.604 | 344 | 19 | 1516 | 0.011 |
| | *ParkingLot* | 8.606 | 91.149 | 310 | 3 | 1335 | 0.004 |
| | *LectureHQ-Reisslein* | 20.148 | 79.038 | 178 | 13 | 216 | 0.02 |
| CIF | *Silence of the Lambs* | | | | | | |
| 101416. | *Terminator I* | 37.943 | 61.374 | 263 | 28 | 4619 | 0.039 |
| No.R.C. | *Snowboard with Comm* | 34.657 | 64.745 | 264 | 32 | 4490 | 0.038 |
| | *Oprah w/o Comm* | 41.718 | 57.65 | 305 | 19 | 1518 | 0.033 |
| | *ParkingLot* | 17.177 | 81.819 | 234 | 3 | 1400 | 0.014 |
| | *LectureHQ-Reisslein* | 35.213 | 62.065 | 113 | 12 | 231 | 0.04 |
| CIF | *Silence of the Lambs* | | | | | | |
| 242424. | *Terminator I* | 50.967 | 48.259 | 260 | 27 | 4830 | 0.046 |
| No.R.C. | *Snowboard with Comm* | 48.548 | 50.625 | 250 | 31 | 4647 | 0.044 |
| | *Oprah w/o Comm* | 58.485 | 40.634 | 263 | 19 | 1549 | 0.042 |
| | *ParkingLot* | 32.494 | 65.911 | 224 | 3 | 1524 | 0.025 |
| | *LectureHQ-Reisslein* | 51.732 | 45.687 | 126 | 10 | 283 | 0.039 |
| CIF | *Silence of the Lambs* | | | | | | |
| 303030. | *Terminator I* | 56.672 | 42.498 | 261 | 26 | 4962 | 0.047 |
| No.R.C. | *Snowboard with Comm* | 55.782 | 43.292 | 248 | 30 | 4783 | 0.046 |
| | *Oprah w/o Comm* | 64.72 | 34.298 | 249 | 18 | 1609 | 0.046 |
| | *ParkingLot* | 41.996 | 56.091 | 222 | 3 | 1616 | 0.032 |
| | *LectureHQ-Reisslein* | 58.787 | 38.733 | 137 | 10 | 288 | 0.04 |
| CIF | *Silence of the Lambs* | | | | | | |
| R.C. | *Terminator I* | 57.384 | 41.788 | 261 | 26 | 4980 | 0.048 |
| 64kbps | *Snowboard with Comm* | 56.709 | 42.381 | 249 | 30 | 4808 | 0.046 |
| | *Oprah w/o Comm* | 65.341 | 33.678 | 249 | 18 | 1588 | 0.046 |
| | *ParkingLot* | 42.981 | 55.122 | 223 | 3 | 1616 | 0.032 |
| | *LectureHQ-Reisslein* | 59.416 | 38.15 | 139 | 9 | 303 | 0.04 |
| CIF | *Silence of the Lambs* | | | | | | |
| R.C. | *Terminator I* | 57.382 | 41.79 | 261 | 26 | 4980 | 0.048 |
| 128kbps | *Snowboard with Comm* | 56.708 | 42.382 | 249 | 30 | 4809 | 0.046 |
| | *Oprah w/o Comm* | 65.34 | 33.679 | 249 | 18 | 1588 | 0.046 |
| | *ParkingLot* | 42.981 | 55.123 | 223 | 3 | 1616 | 0.032 |
| | *LectureHQ-Reisslein* | 59.414 | 38.152 | 139 | 9 | 303 | 0.04 |
| CIF | *Silence of the Lambs* | | | | | | |
| R.C. | *Terminator I* | 57.287 | 41.89 | 262 | 26 | 4976 | 0.048 |
| 256kbps | *Snowboard with Comm* | 56.57 | 42.526 | 249 | 30 | 4806 | 0.046 |
| | *Oprah w/o Comm* | 63.383 | 35.692 | 251 | 18 | 1590 | 0.053 |
| | *ParkingLot* | 42.945 | 55.154 | 223 | 3 | 1616 | 0.032 |

Table 8: Overview of Motion Vector Statistics of single-layer traces

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | *LectureHQ-Reisslein* | 44.78 | 52.588 | 139 | 11 | 258 | 0.059 |
| CIF | *Silence of the Lambs* | | | | | | |
| R.C. | *Terminator I* | 24.709 | 74.907 | 291 | 29 | 4470 | 0.027 |
| 512kbps | *Snowboard with Comm* | 22.605 | 77.148 | 329 | 32 | 4408 | 0.028 |
| | *Oprah w/o Comm* | 20.411 | 79.348 | 347 | 18 | 1570 | 0.012 |
| | *ParkingLot* | 33.333 | 65.035 | 238 | 3 | 1607 | 0.038 |
| | *LectureHQ-Reisslein* | 28.723 | 70.56 | 245 | 12 | 218 | 0.038 |
| CIF | *Silence of the Lambs* | | | | | | |
| R.C. | *Terminator I* | 24.709 | 74.907 | 291 | 29 | 4470 | 0.027 |
| 1024kbps | *Snowboard with Comm* | 22.605 | 77.148 | 329 | 32 | 4408 | 0.028 |
| | *Oprah w/o Comm* | 20.411 | 79.348 | 347 | 18 | 1570 | 0.012 |
| | *ParkingLot* | 14.882 | 84.737 | 309 | 3 | 1349 | 0.015 |
| | *LectureHQ-Reisslein* | 14.203 | 85.535 | 319 | 13 | 205 | 0.01 |

Table 9: Overview of Motion Vector Statistics of single-layer traces

| Format | Sequence | | | | | | |
|---|---|---|---|---|---|---|---|
| CIF | *Silence of the Lambs* | | | | | | |
| 040404. | *Terminator I* | 9.044 | 0.006 | 11893.53 | 8.139 | 1.1 | 9.044 |
| No.R.C. | *Snowboard with Comm* | 6.289 | 0.003 | 12133.693 | 6.811 | 1.068 | 6.289 |
| | *Oprah w/o Comm* | 4.239 | 0.001 | 11973.057 | 13.704 | 1.045 | 4.239 |
| | *ParkingLot* | 2.098 | 0 | 11945.446 | 23.312 | 1.022 | 2.098 |
| | *LectureHQ-Reisslein* | 6.967 | 0.002 | 11493.795 | 4.259 | 1.076 | 6.967 |
| CIF | *Silence of the Lambs* | 31.172 | 0.046 | 11022.237 | 2.73 | 1.464 | 31.172 |
| 040608. | *Terminator I* | 20.291 | 0.024 | 11619.134 | 4.235 | 1.259 | 20.291 |
| No.R.C. | *Snowboard with Comm* | 17.386 | 0.022 | 11844.829 | 5.002 | 1.213 | 17.386 |
| | *Oprah w/o Comm* | 13.235 | 0.006 | 11841.854 | 6.538 | 1.154 | 13.235 |
| | *ParkingLot* | 5.703 | 0.002 | 11306.089 | 11.362 | 1.062 | 5.703 |
| | *LectureHQ-Reisslein* | 19.581 | 0.019 | 6823.218 | 3.544 | 1.252 | 19.581 |
| CIF | *Silence of the Lambs* | 35.357 | 0.044 | 14024.687 | 2.416 | 1.57 | 35.357 |
| 060810. | *Terminator I* | 24.709 | 0.028 | 12412.638 | 3.43 | 1.335 | 24.709 |
| No.R.C. | *Snowboard with Comm* | 22.605 | 0.028 | 11267.193 | 3.886 | 1.296 | 22.605 |
| | *Oprah w/o Comm* | 20.411 | 0.012 | 12014.877 | 4.127 | 1.26 | 20.411 |
| | *ParkingLot* | 8.456 | 0.003 | 11619.94 | 8.536 | 1.095 | 8.456 |
| | *LectureHQ-Reisslein* | 21.679 | 0.024 | 6572.06 | 3.488 | 1.292 | 21.679 |
| CIF | *Silence of the Lambs* | | | | | | |
| 101010. | *Terminator I* | 25.106 | 0.026 | 12691.966 | 3.425 | 1.342 | 25.106 |
| No.R.C. | *Snowboard with Comm* | 20.878 | 0.022 | 11965.309 | 4.153 | 1.268 | 20.878 |
| | *Oprah w/o Comm* | 21.153 | 0.01 | 11883.948 | 4.035 | 1.272 | 21.153 |
| | *ParkingLot* | 8.606 | 0.004 | 11147.313 | 8.755 | 1.097 | 8.606 |
| | *LectureHQ-Reisslein* | 20.148 | 0.02 | 8103.055 | 3.661 | 1.265 | 20.148 |
| CIF | *Silence of the Lambs* | | | | | | |
| 101416. | *Terminator I* | 37.943 | 0.04 | 13454.777 | 2.288 | 1.629 | 37.943 |
| No.R.C. | *Snowboard with Comm* | 34.657 | 0.039 | 13236.318 | 2.526 | 1.544 | 34.657 |
| | *Oprah w/o Comm* | 41.718 | 0.033 | 15120.555 | 2.048 | 1.734 | 41.718 |
| | *ParkingLot* | 17.177 | 0.014 | 18720.211 | 4.15 | 1.222 | 17.177 |
| | *LectureHQ-Reisslein* | 35.213 | 0.041 | 8932.984 | 2.368 | 1.611 | 35.213 |
| CIF | *Silence of the Lambs* | | | | | | |
| 242424. | *Terminator I* | 50.967 | 0.047 | 13261.357 | 1.718 | 2.071 | 50.967 |
| No.R.C. | *Snowboard with Comm* | 48.548 | 0.044 | 13706.988 | 1.81 | 1.974 | 48.548 |
| | *Oprah w/o Comm* | 58.485 | 0.042 | 12255.483 | 1.473 | 2.459 | 58.485 |
| | *ParkingLot* | 32.494 | 0.026 | 19245.996 | 2.433 | 1.516 | 32.494 |
| | *LectureHQ-Reisslein* | 51.732 | 0.04 | 10621.169 | 1.659 | 2.187 | 51.732 |
| CIF | *Silence of the Lambs* | | | | | | |
| 303030. | *Terminator I* | 56.672 | 0.048 | 13110.538 | 1.555 | 2.351 | 56.672 |
| No.R.C. | *Snowboard with Comm* | 55.782 | 0.046 | 13631.753 | 1.583 | 2.308 | 55.782 |

Table 9: Overview of Motion Vector Statistics of single-layer traces

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | *Oprah w/o Comm* | 64.72 | 0.046 | 11328.471 | 1.346 | 2.913 | 64.720 |
| | *ParkingLot* | 41.996 | 0.033 | 19097.676 | 1.925 | 1.782 | 41.996 |
| | *LectureHQ-Reisslein* | 58.787 | 0.041 | 11002.396 | 1.452 | 2.579 | 58.787 |
| CIF | *Silence of the Lambs* | | | | | | |
| R.C. | *Terminator I* | 57.384 | 0.048 | 13071.349 | 1.525 | 2.391 | 57.384 |
| 64kbps | *Snowboard with Comm* | 56.709 | 0.047 | 13396.801 | 1.572 | 2.358 | 56.709 |
| | *Oprah w/o Comm* | 65.341 | 0.046 | 11231.207 | 1.328 | 2.966 | 65.341 |
| | *ParkingLot* | 42.981 | 0.033 | 18880.533 | 1.892 | 1.813 | 42.981 |
| | *LectureHQ-Reisslein* | 59.416 | 0.041 | 11055.624 | 1.44 | 2.619 | 59.416 |
| CIF | *Silence of the Lambs* | | | | | | |
| R.C. | *Terminator I* | 57.382 | 0.048 | 13065.408 | 1.525 | 2.391 | 57.382 |
| 128kbps | *Snowboard with Comm* | 56.708 | 0.047 | 13396.696 | 1.572 | 2.358 | 56.708 |
| | *Oprah w/o Comm* | 65.34 | 0.046 | 11232.178 | 1.328 | 2.966 | 65.340 |
| | *ParkingLot* | 42.981 | 0.033 | 18881.047 | 1.892 | 1.813 | 42.981 |
| | *LectureHQ-Reisslein* | 59.414 | 0.041 | 11057.287 | 1.44 | 2.619 | 59.414 |
| CIF | *Silence of the Lambs* | | | | | | |
| R.C. | *Terminator I* | 57.287 | 0.049 | 12996.505 | 1.528 | 2.385 | 57.287 |
| 256kbps | *Snowboard with Comm* | 56.57 | 0.047 | 13380.42 | 1.576 | 2.351 | 56.570 |
| | *Oprah w/o Comm* | 63.383 | 0.053 | 10908.215 | 1.369 | 2.801 | 63.383 |
| | *ParkingLot* | 42.945 | 0.033 | 18897.348 | 1.893 | 1.812 | 42.945 |
| | *LectureHQ-Reisslein* | 44.78 | 0.061 | 8438.415 | 1.915 | 1.901 | 44.780 |
| CIF | *Silence of the Lambs* | | | | | | |
| R.C. | *Terminator I* | 24.709 | 0.028 | 12412.638 | 3.43 | 1.335 | 24.709 |
| 512kbps | *Snowboard with Comm* | 22.605 | 0.028 | 11267.193 | 3.886 | 1.296 | 22.605 |
| | *Oprah w/o Comm* | 20.411 | 0.012 | 12014.877 | 4.127 | 1.26 | 20.411 |
| | *ParkingLot* | 33.333 | 0.039 | 18363.627 | 2.44 | 1.537 | 33.333 |
| | *LectureHQ-Reisslein* | 28.723 | 0.039 | 8295.44 | 2.956 | 1.417 | 28.723 |
| CIF | *Silence of the Lambs* | | | | | | |
| R.C. | *Terminator I* | 24.709 | 0.028 | 12412.638 | 3.43 | 1.335 | 24.709 |
| 1024kbps | *Snowboard with Comm* | 22.605 | 0.028 | 11267.193 | 3.886 | 1.296 | 22.605 |
| | *Oprah w/o Comm* | 20.411 | 0.012 | 12014.877 | 4.127 | 1.26 | 20.411 |
| | *ParkingLot* | 14.882 | 0.016 | 12162.299 | 4.951 | 1.18 | 14.882 |
| | *LectureHQ-Reisslein* | 14.203 | 0.01 | 10417.805 | 5.379 | 1.169 | 14.203 |

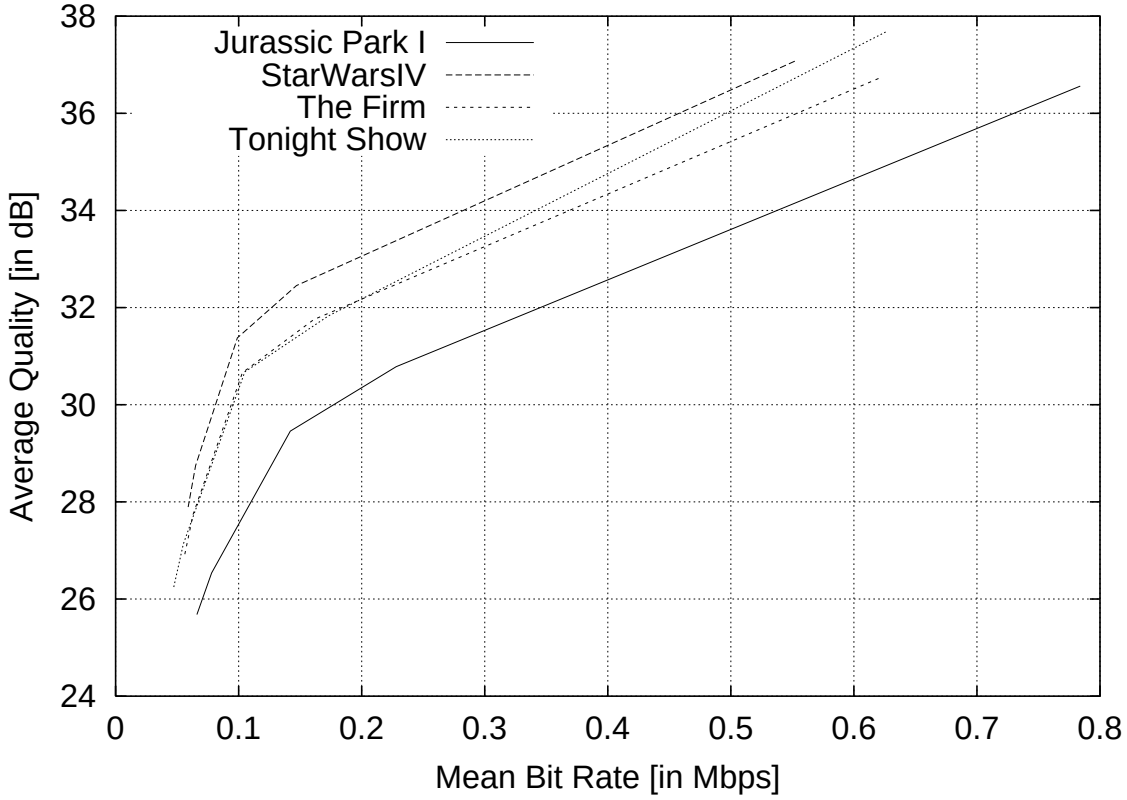



Figure 19: Rate-distortion plot for single-layer QCIF video.

# 5 Discussion

One of the first questions that we asked in our analysis of single layer video encodings was if it would be possible to generate higher or lower quality video traces by simply scaling the frame sizes in the traces by a constant, namely the ratio of the mean frame sizes of the higher and lower quality video encodings. For instance, knowing that the ratio of the mean frame size between the high and low quality encodings of *Silence of the Lambs* is 8.797, could we then multiply the frames sizes in the low quality trace by 8.797 to produce a statistically usable trace of *Silence of the Lambs* at high quality. In order to answer this question, we took the trace of the low quality single layer encoding of *Silence of the Lambs* and multiplied all of the frames by this ratio, 8.797, and processed this new trace file using the same statistical tools that were used to analyze the original trace file. We found that this scaling does not generate statistically valid simulations of different quality video data; when we compared the statistics of the generated data with the actual data, the upscaled data varied considerably in a few key

areas. First, since lower quality level encodings demonstrate a significantly larger variability, the variance and the coefficient of variation were considerably different, with the variance and the coefficient of variation of the upscaled data closely matching the statistics of the original lower quality encoding.

These observations can be verified through mathematical analysis. For example, with a scaling factor of $m$, and an original frame size of $X_n$, the scaled trace has an estimated sample mean $\bar{X}'$ of

$$\begin{aligned} \bar{X}' &= \frac{1}{N}\sum_{n=0}^{N-1} mX_n \\ &= m\bar{X}. \end{aligned} \tag{1}$$

The scaled data has an estimated sample variance ${S_X}'^2$ of

$$\begin{aligned} {S_X}'^2 &= \frac{1}{N-1}\sum_{n=0}^{N-1}(mX_n - m\bar{X})^2 \\ &= \frac{m^2}{N-1}\sum_{n=0}^{N-1}(X_n - \bar{X})^2 \\ &= m^2 S_X^2. \end{aligned} \tag{2}$$

The scaled data has a coefficient of variation $CoV_X'$ of

$$\begin{aligned} {CoV_X}' &= \frac{mS_X}{m\bar{X}} \\ &= CoV_X. \end{aligned} \tag{3}$$

The scaled data has an estimated autocorrelation coefficient $\rho_X(k)'$ for lag $k,\ k = 0, 1, \ldots, N-1$, of

$$\begin{aligned} \rho_X(k)' &= \frac{1}{N-k}\sum_{n=0}^{N-k-1}\frac{(mX_n - m\bar{X})(mX_{n+k} - m\bar{X})}{m^2 S_X^2} \\ &= \frac{1}{N-k}\sum_{n=0}^{N-k-1}\frac{m^2(X_n - \bar{X})(X_{n+k} - \bar{X})}{m^2 S_X^2} \\ &= \frac{1}{N-k}\sum_{n=0}^{N-k-1}\frac{(X_n - \bar{X})(X_{n+k} - \bar{X})}{S_X^2} \\ &= \rho_X(k). \end{aligned} \tag{4}$$

Similarly, the peak-to-mean ratio of the scaled trace is $X'_{max}/\bar{X}' = X_{max}/\bar{X}$. Also, the long range dependence characteristics of the upscaled trace mirrored, almost exactly, the long range dependence of the low quality trace. This is also expected. The scaling of the frame sizes does not remove any long range dependent behavior from the data set, because the data is still just as correlated as it was before scaling.

These same observations hold true if we approach the problem from the other direction. Namely, can we downscale higher quality video trace data to simulate low quality and low bit rate video? The answer is that we would have all of the same problems already discussed for upscaling, i.e., the variance, the coefficient of variation, the peak-to-mean ratio, and the long range dependent data would all resemble the original high quality data. The fundamental insight is, of course, that encodings done at different quality levels produce traces with different statistics. This insight is particularly important for the analysis of traffic over wireless networks. Often when planning to meet a level of service in a wireless network, low bit rate data streams need to be generated for testing and performance evaluation. Wireless networks typically allow only for the transmission of low bit rate video. Thus, when evaluating the performance of protocols and mechanisms for wireless video transmission, it is important to use traces of actual low bit rate encoded video. Higher bit rate video can not simply be scaled down to preform this evaluation because the higher bit rate encoded video is statistically different — in particular, less bursty — from the lower bit rate video and, therefore, does not adequately reflect the network performance.

# 6 Conclusions

In this initial analysis of the frame size and frame quality traces of single layer encoded video we have observed several interesting phenomena. For instance, we observed that the coefficient of variation and the peak-to-mean ratio for videos at high quality are generally smaller than the values observed for medium quality video, which are in turn larger than the values observed for low quality video encodings. This "hump" in the $CoV_X$ and $X_{\max}/\bar{X}$ is to the best of our knowledge a new insight. Our previous study [7] uncovered only an increase of the $CoV_X$ and $X_{\max}/\bar{X}$ for decreasing quality. That previous study considered only quantization parameters in the range from 4 to 16. Consequently, we observed only the first half of the "hump." In this study, on the other hand, we consider quantization parameters from 4 to 30; whereby 31 is the largest valid quantization parameter for the employed MPEG-4 software encoder. By taking this full range of quantization parameters into consideration, we uncover here the "hump" behavior of the $CoV_X$ and $X_{\max}/\bar{X}$. In contrast to this "hump" behavior of the $CoV_X$ and $X_{\max}/\bar{X}$, the longe range dependence properties appear to be consistently strong for all

quality levels of the videos encoded without rate control.

Another interesting observation is that the encodings with rate control tend to have large (but rare) outliers in their frame (and GoP) sizes, which might give rise to heavy tail behavior in networks.

Also, the traffic quality correlations exhibit number of interesting behaviors. These and all other observations from this first large scale joint study of long frame size and frame quality traces call for detailed investigations, which we are currently undertaking. Importantly, all our data suggests that video trace data can not simply be scaled (either up or down) by a constant to obtain statistically valid lower or higher bit rate video trace data since lower bit rate video is more bursty than higher bit rate data, and scaling the frame sizes does not change the variability of the data. This insight has important implications on the testing and performance evaluation of wireless networks, where low bit rate data is needed. It is important that traces of actual low bit rate encoded video data are used in testing so that performance and quality of service models can be verified accurately.

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