

# 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

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

Table 1: *continued*

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

Table 1: *continued*

Enc. M.	Video	Compr. ratio YUV:MP4	Frame Size			Bit Rate	
			Mean $\bar{X}$ [kbyte]	$CoV_{\bar{X}}$ $S_{\bar{X}}/\bar{X}$	Peak/Mean $X_{\max}/\bar{X}$	Mean $\bar{X}/T$ [Mbps]	Peak $X_{\max}/T$ [Mbps]
QCIF	<i>Citizen Kane</i>	71.206	0.534	1.401	17.749	0.128	2.274
R.C.	<i>Die Hard I</i>	71.204	0.534	1.169	20.918	0.128	2.680
128 kbps	<i>Jurassic Park I</i>	71.205	0.534	1.295	20.774	0.128	2.662
	<i>Silence of the Lambs</i>	71.206	0.534	1.117	33.430	0.128	4.284
	<i>Star Wars IV</i>	71.206	0.534	1.132	22.063	0.128	2.827
	<i>Star Wars V</i>	71.206	0.534	1.132	26.592	0.128	3.407
	<i>The Firm</i>	71.206	0.534	1.286	22.291	0.128	2.856
	<i>Terminator I</i>	71.086	0.535	1.130	31.122	0.128	3.995
	<i>Total Recall</i>	71.207	0.534	1.182	19.649	0.128	2.518
	<i>Aladdin</i>	71.206	0.534	1.066	50.883	0.128	6.520
	<i>Cinderella</i>	71.206	0.534	1.186	41.940	0.128	5.374
	<i>Baseball with Comm</i>	71.205	0.534	1.119	26.185	0.128	3.355
	<i>Snowboard with Comm</i>	71.207	0.534	1.077	39.932	0.128	5.117
	<i>Oprah w/o Comm</i>	71.206	0.534	1.211	15.679	0.128	2.009
	<i>Tonight Show w/o Comm</i>	71.206	0.534	1.358	20.366	0.128	2.610
	<i>Lecture-Gupta</i>	71.206	0.534	1.604	19.677	0.128	2.521
	<i>Lecture-Reisslein</i>	71.206	0.534	1.293	25.650	0.128	3.287
QCIF	<i>Citizen Kane</i>	35.622	1.067	1.102	11.164	0.256	2.859
R.C.	<i>Die Hard I</i>	35.622	1.067	0.978	8.981	0.256	2.300
256 kbps	<i>Jurassic Park I</i>	35.622	1.067	1.106	9.345	0.256	2.394
	<i>Silence of the Lambs</i>	35.622	1.067	0.904	8.006	0.256	2.051
	<i>Star Wars IV</i>	35.622	1.067	0.927	9.659	0.256	2.474
	<i>Star Wars V</i>	35.622	1.067	0.961	6.890	0.256	1.765
	<i>The Firm</i>	35.621	1.067	1.046	10.775	0.256	2.760
	<i>Terminator I</i>	35.622	1.067	1.009	11.874	0.256	3.041
	<i>Total Recall</i>	35.622	1.067	1.001	8.991	0.256	2.303
	<i>Aladdin</i>	35.622	1.067	1.005	13.086	0.256	3.352
	<i>Cinderella</i>	35.622	1.067	1.010	10.049	0.256	2.574
	<i>Baseball with Comm</i>	35.622	1.067	0.924	10.565	0.256	2.706
	<i>Snowboard with Comm</i>	35.622	1.067	0.950	9.911	0.256	2.538
	<i>Oprah w/o Comm</i>	35.622	1.067	0.987	8.445	0.256	2.163
	<i>Tonight Show w/o Comm</i>	35.622	1.067	1.081	8.479	0.256	2.172
	<i>Lecture-Gupta</i>	35.621	1.067	1.090	9.192	0.256	2.354
	<i>Lecture-Reisslein</i>	35.622	1.067	0.989	7.426	0.256	1.902
CIF	<i>Silence of the Lambs</i>	22.735	6.688	0.742	8.271	1.605	13.277
H.Q. No R.C.							
CIF	<i>Silence of the Lambs</i>	116.402	1.306	1.326	18.782	0.314	5.889
M.Q. No R.C.							
CIF	<i>Silence of the Lambs</i>	160.877	0.945	0.774	13.009	0.227	2.951
L.Q. No R.C.							
CIF	<i>Silence of the Lambs</i>	162.275	0.937	0.762	12.901	0.225	2.901
R.C. 64 kbps							
CIF	<i>Silence of the Lambs</i>	162.251	0.937	0.763	12.899	0.225	2.901
R.C. 128 kbps							
CIF	<i>Silence of the Lambs</i>	137.562	1.105	0.933	49.493	0.265	13.131
R.C. 256 kbps							

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

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

Table 2: *continued*

Enc. M.	Video	GoP Size			Bit Rate	
		Mean $\bar{Y}$ [kbyte]	$CoV_{\bar{Y}}$ $S_{\bar{Y}}/\bar{Y}$	Peak/Mean $Y_{\max}/\bar{Y}$	Mean $\bar{Y}/(GT)$ [Mbps]	Peak $Y_{\max}/(GT)$ [Mbps]
	<i>The Firm</i>	2.785	0.433	3.510	0.056	0.196
	<i>Terminator I</i>	3.908	0.438	4.492	0.078	0.351
	<i>Total Recall</i>	3.400	0.414	3.218	0.068	0.219
	<i>Aladdin</i>	4.538	0.452	4.305	0.091	0.391
	<i>Cinderella</i>	3.720	0.438	8.350	0.074	0.621
	<i>Baseball with Comm</i>	3.710	0.410	3.794	0.074	0.282
	<i>Snowboard with Comm</i>	4.702	0.383	4.851	0.094	0.456
	<i>Oprah w/o Comm</i>	3.406	0.360	3.866	0.068	0.263
	<i>Tonight Show w/o Comm</i>	2.325	0.671	5.174	0.047	0.241
	<i>Lecture-Gupta</i>	3.511	0.240	2.867	0.070	0.201
	<i>Lecture-Reisslein</i>	3.573	0.407	3.644	0.071	0.260
QCIF	<i>Citizen Kane</i>	3.207	0.354	13.905	0.064	0.892
R.C	<i>Die Hard I</i>	3.482	0.389	2.991	0.070	0.208
64 kbps	<i>Jurassic Park I</i>	3.316	0.405	6.199	0.066	0.411
	<i>Silence of the Lambs</i>	3.207	0.387	12.643	0.064	0.811
	<i>Star Wars IV</i>	3.227	0.421	17.842	0.065	1.152
	<i>Star Wars V</i>	3.317	0.460	13.627	0.066	0.904
	<i>The Firm</i>	3.207	0.370	7.914	0.064	0.508
	<i>Terminator I</i>	3.912	0.437	12.037	0.078	0.942
	<i>Total Recall</i>	3.425	0.459	18.510	0.069	1.268
	<i>Aladdin</i>	4.450	0.447	6.608	0.089	0.588
	<i>Cinderella</i>	3.683	0.427	8.056	0.074	0.594
	<i>Baseball with Comm</i>	3.685	0.398	3.747	0.074	0.276
	<i>Snowboard with Comm</i>	4.608	0.378	4.763	0.092	0.439
	<i>Oprah w/o Comm</i>	3.354	0.379	8.861	0.067	0.594
	<i>Tonight Show w/o Comm</i>	3.235	0.428	5.034	0.065	0.326
	<i>Lecture-Gupta</i>	3.411	0.238	4.833	0.068	0.330
	<i>Lecture-Reisslein</i>	3.626	0.334	3.368	0.073	0.244
QCIF	<i>Citizen Kane</i>	6.407	0.091	3.539	0.128	0.453
R.C.	<i>Die Hard I</i>	6.407	0.117	2.841	0.128	0.364
128 kbps	<i>Jurassic Park I</i>	6.407	0.129	5.198	0.128	0.666
	<i>Silence of the Lambs</i>	6.407	0.103	5.678	0.128	0.728
	<i>Star Wars IV</i>	6.407	0.089	3.566	0.128	0.457
	<i>Star Wars V</i>	6.407	0.118	4.842	0.128	0.620
	<i>The Firm</i>	6.407	0.089	3.327	0.128	0.426
	<i>Terminator I</i>	6.417	0.165	4.181	0.128	0.537
	<i>Total Recall</i>	6.407	0.106	2.626	0.128	0.336
	<i>Aladdin</i>	6.407	0.277	9.691	0.128	1.242
	<i>Cinderella</i>	6.407	0.206	7.652	0.128	0.980
	<i>Baseball with Comm</i>	6.407	0.160	4.180	0.128	0.536
	<i>Snowboard with Comm</i>	6.407	0.238	6.087	0.128	0.780
	<i>Oprah w/o Comm</i>	6.407	0.091	2.562	0.128	0.328
	<i>Tonight Show w/o Comm</i>	6.407	0.107	3.457	0.128	0.443
	<i>Lecture-Gupta</i>	6.407	0.092	5.018	0.128	0.643
	<i>Lecture-Reisslein</i>	6.407	0.091	3.654	0.128	0.468
QCIF	<i>Citizen Kane</i>	12.806	0.043	1.727	0.256	0.442
R.C.	<i>Die Hard I</i>	12.807	0.034	1.410	0.256	0.361
256 kbps	<i>Jurassic Park I</i>	12.807	0.039	1.529	0.256	0.392
	<i>Silence of the Lambs</i>	12.806	0.030	1.572	0.256	0.403
	<i>Star Wars IV</i>	12.807	0.031	1.423	0.256	0.364
	<i>Star Wars V</i>	12.807	0.035	1.409	0.256	0.361
	<i>The Firm</i>	12.807	0.034	1.395	0.256	0.357
	<i>Terminator I</i>	12.807	0.053	1.989	0.256	0.509
	<i>Total Recall</i>	12.807	0.036	1.444	0.256	0.370
	<i>Aladdin</i>	12.806	0.072	1.766	0.256	0.452
	<i>Cinderella</i>	12.806	0.063	2.387	0.256	0.611
	<i>Baseball with Comm</i>	12.807	0.038	1.491	0.256	0.382
	<i>Snowboard with Comm</i>	12.806	0.059	2.070	0.256	0.530
	<i>Oprah w/o Comm</i>	12.807	0.024	1.336	0.256	0.342
	<i>Tonight Show w/o Comm</i>	12.807	0.037	1.486	0.256	0.381



Table 2: *continued*

Enc. M.	Video	GoP Size			Bit Rate	
		Mean $\bar{Y}$ [kbyte]	$CoV_{\bar{Y}}$ $S_{\bar{Y}}/\bar{Y}$	Peak/Mean $Y_{\max}/\bar{Y}$	Mean $\bar{Y}/(GT)$ [Mbps]	Peak $Y_{\max}/(GT)$ [Mbps]
	<i>Lecture-Gupta</i>	12.807	0.041	1.312	0.256	0.336
	<i>Lecture-Reisslein</i>	12.807	0.030	1.309	0.256	0.335
CIF H.Q. No R.C.	<i>Silence of the Lambs</i>	80.261	0.620	6.290	1.605	10.096
CIF M.Q. No R.C.	<i>Silence of the Lambs</i>	15.676	0.835	9.653	0.314	3.026
CIF L.Q. No R.C.	<i>Silence of the Lambs</i>	11.343	0.542	6.333	0.227	1.437
CIF R.C. 64 kbps	<i>Silence of the Lambs</i>	11.245	0.533	6.208	0.225	1.396
CIF R.C. 128 kbps	<i>Silence of the Lambs</i>	11.247	0.533	6.207	0.225	1.396
CIF R.C. 256 kbps	<i>Silence of the Lambs</i>	13.265	0.458	9.908	0.265	2.629

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  $X_n$ ,  $n = 0, \dots, N-1$ , 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  $Y_m$ ,  $m = 0, \dots, N/G - 1$ , 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  $a$ .

Enc. M.	Video	Aggregation level $a$ [frames]											
		1	12	24	48	96	192	300	396	504	600	696	792
QCIF	<i>Citizen Kane</i>	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.	<i>Citizen Kane</i>		1.180	1.170	1.169	1.053	0.946	0.884	0.885	0.887	0.884	0.987	0.806

Table 3: continued

Enc. M.	Video	Aggregation level $\alpha$ [frames]											
		1	12	24	48	96	192	300	396	504	600	696	792
No.R.C	<i>Die Hard I</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
	<i>Die Hard I</i>		1.125	1.076	0.997	0.892	0.804	0.776	0.804	0.816	0.802	0.809	0.768
	<i>Jurassic Park I</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
	<i>Jurassic Park I</i>		1.207	1.207	1.115	1.068	0.991	0.951	0.934	0.951	0.930	0.827	0.848
	<i>Silence of the Lambs</i>	0.977	0.905	0.889	0.890	0.911	0.923	0.903	0.898	0.805	0.795	0.828	0.752
	<i>Silence of the Lambs</i>		1.203	1.250	1.168	1.061	1.018	1.011	1.006	1.084	1.040	1.074	1.120
	<i>Star Wars IV</i>	0.927	0.857	0.849	0.839	0.826	0.815	0.837	0.834	0.851	0.857	0.881	0.874
	<i>Star Wars IV</i>		1.123	1.109	1.061	1.028	0.965	0.961	1.005	0.960	1.014	0.909	1.029
	<i>Star Wars V</i>	0.958	0.875	0.849	0.853	0.834	0.826	0.801	0.789	0.846	0.780	0.817	0.752
	<i>Star Wars V</i>		1.249	1.206	1.079	1.012	0.994	0.958	0.909	0.914	0.901	0.814	0.772
	<i>The Firm</i>	0.975	0.875	0.861	0.845	0.824	0.811	0.792	0.812	0.754	0.742	0.736	0.700
	<i>The Firm</i>		1.168	1.196	1.144	1.096	1.085	1.033	1.057	0.990	1.043	1.026	1.009
	<i>Terminator I</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
	<i>Terminator I</i>		1.113	1.085	1.029	1.017	0.999	0.991	0.969	1.020	0.949	1.011	0.949
	<i>Total Recall</i>	0.920	0.870	0.865	0.848	0.853	0.836	0.830	0.821	0.840	0.823	0.822	0.829
	<i>Total Recall</i>		1.135	1.121	1.053	0.995	0.993	0.930	0.985	0.876	0.918	0.866	0.895
	<i>Aladdin</i>	0.926	0.875	0.860	0.866	0.854	0.870	0.873	0.824	0.810	0.799	0.780	0.729
	<i>Aladdin</i>		1.082	1.037	0.969	0.913	0.944	0.938	0.977	0.996	1.107	1.022	1.016
	<i>Cinderella</i>	0.916	0.848	0.835	0.845	0.856	0.857	0.880	0.864	0.838	0.866	0.821	0.880
	<i>Cinderella</i>		1.136	1.079	1.000	0.968	0.983	0.995	1.023	1.034	1.018	1.053	0.973
	<i>Baseball with Comm</i>	0.933	0.825	0.819	0.798	0.810	0.838	0.855	0.876	0.810	0.812	0.876	0.858
	<i>Baseball with Comm</i>		1.121	1.112	1.020	0.986	0.877	0.790	0.810	0.797	0.811	0.858	0.828
	<i>Snowboard with Comm</i>	0.897	0.786	0.765	0.742	0.713	0.691	0.695	0.699	0.730	0.739	0.668	0.740
	<i>Snowboard with Comm</i>		1.199	1.115	0.930	0.935	0.868	0.804	0.754	0.730	0.787	0.660	0.746
	<i>Oprah w/o Comm</i>	0.983	0.875	0.864	0.858	0.882	0.887	0.982	0.921	0.986	0.988	0.898	0.901
	<i>Oprah w/o Comm</i>		1.231	1.213	1.144	1.022	1.042	1.098	1.056	1.051	1.017	1.074	1.193
	<i>Tonight Show w/o Comm</i>	0.914	0.906	0.921	0.917	0.919	0.905	0.958	0.916	0.977	0.981	0.948	0.988
	<i>Tonight Show w/o Comm</i>		1.180	1.228	1.245	1.245	1.226	1.227	1.265	1.328	1.286	1.321	1.281
	<i>Lecture-Gupta</i>	0.990	0.996	0.999	0.978	0.955	0.928	0.970	0.923	0.949	0.953	0.924	0.919
	<i>Lecture-Gupta</i>		1.318	1.265	1.269	1.099	0.903	0.979	1.079	0.978	1.008	1.198	1.196
	<i>Lecture-Reisslein</i>	1.036	0.969	0.957	0.948	0.935	0.917	0.891	0.935	0.936	0.876	0.937	0.938
	<i>Lecture-Reisslein</i>		1.339	1.305	1.226	1.195	1.138	1.161	1.208	1.246	1.288	1.303	1.320
QCIF	<i>Jurassic Park I</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.	<i>Jurassic Park I</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.	<i>Star Wars IV</i>	0.881	0.852	0.846	0.831	0.821	0.834	0.840	0.836	0.818	0.830	0.860	0.876
	<i>Star Wars IV</i>		1.031	1.049	1.037	1.024	0.978	0.951	0.942	0.941	0.980	0.930	0.965
	<i>The Firm</i>	0.937	0.894	0.892	0.861	0.836	0.832	0.836	0.853	0.797	0.770	0.750	0.749
	<i>The Firm</i>		1.061	1.113	1.104	1.074	1.112	1.045	1.069	1.072	1.096	1.039	1.125
	<i>Tonight Show w/o Comm</i>	0.825	0.870	0.868	0.870	0.879	0.877	0.952	0.896	0.938	0.982	0.952	1.003
	<i>Tonight Show w/o Comm</i>		1.121	1.161	1.153	1.157	1.145	1.132	1.221	1.262	1.245	1.357	1.266
QCIF	<i>Citizen Kane</i>	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.	<i>Citizen Kane</i>		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.	<i>Die Hard I</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
	<i>Die Hard I</i>		1.036	1.058	0.984	0.921	0.864	0.802	0.908	0.818	0.737	0.777	0.774
	<i>Jurassic Park I</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
	<i>Jurassic Park I</i>		1.099	1.156	1.090	1.017	0.985	0.921	0.928	0.937	0.892	0.799	0.882
	<i>Silence of the Lambs</i>	0.858	0.912	0.895	0.889	0.881	0.888	0.887	0.853	0.831	0.806	0.808	0.776
	<i>Silence of the Lambs</i>		1.053	1.131	1.106	1.034	1.008	1.030	1.006	1.034	1.089	1.061	1.123
	<i>Star Wars IV</i>	0.822	0.846	0.843	0.820	0.816	0.836	0.843	0.836	0.818	0.829	0.852	0.885
	<i>Star Wars IV</i>		0.998	1.021	1.015	1.002	0.978	0.931	0.922	0.917	0.961	0.952	0.923
	<i>Star Wars V</i>	0.861	0.882	0.861	0.855	0.849	0.831	0.815	0.818	0.873	0.854	0.899	0.848
	<i>Star Wars V</i>		1.113	1.118	1.040	0.984	0.974	0.951	0.917	0.871	0.927	0.849	0.896
	<i>The Firm</i>	0.868	0.891	0.881	0.855	0.832	0.826	0.844	0.858	0.802	0.778	0.752	0.753
	<i>The Firm</i>		1.019	1.070	1.080	1.067	1.102	1.005	1.045	1.067	1.066	1.017	1.090
	<i>Terminator I</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
	<i>Terminator I</i>		1.044	1.068	1.032	1.030	0.969	0.998	1.010	0.991	0.998	1.057	0.969
	<i>Total Recall</i>	0.826	0.836	0.818	0.800	0.795	0.770	0.763	0.748	0.750	0.796	0.752	0.710
	<i>Total Recall</i>		1.033	1.057	1.034	0.994	1.015	0.983	0.978	0.853	0.926	0.888	0.991
	<i>Aladdin</i>	0.861	0.881	0.866	0.875	0.875	0.898	0.911	0.841	0.869	0.855	0.796	0.774
	<i>Aladdin</i>		1.020	0.994	0.953	0.922	0.985	0.947	0.991	1.017	1.044	1.037	1.044
	<i>Cinderella</i>	0.821	0.814	0.791	0.792	0.791	0.793	0.789	0.760	0.735	0.724	0.710	0.755
	<i>Cinderella</i>		1.044	1.035	0.971	0.942	0.928	0.974	0.942	0.983	0.977	0.976	0.876
	<i>Baseball with Comm</i>	0.809	0.788	0.772	0.732	0.727	0.752	0.783	0.798	0.798	0.815	0.876	0.864
	<i>Baseball with Comm</i>		1.037	1.036	1.019	0.982	0.819	0.749	0.758	0.749	0.719	0.797	0.726
	<i>Snowboard with Comm</i>	0.821	0.772	0.742	0.713	0.674	0.634	0.637	0.648	0.677	0.686	0.602	0.663
	<i>Snowboard with Comm</i>		1.102	1.058	0.941	0.926	0.835	0.767	0.730	0.699	0.781	0.676	0.729
	<i>Oprah w/o Comm</i>	0.820	0.851	0.834	0.817	0.820	0.825	0.877	0.800	0.821	0.895	0.799	0.801
	<i>Oprah w/o Comm</i>		1.095	1.107	1.079	1.013	1.003	1.013	1.002	0.990	0.984	0.972	1.035
	<i>Tonight Show w/o Comm</i>	0.761	0.865	0.862	0.868	0.879	0.880	0.958	0.904	0.961	1.006	0.946	1.004
	<i>Tonight Show w/o Comm</i>		1.076	1.117	1.125	1.149	1.120	1.108	1.208	1.237	1.222	1.304	1.262
	<i>Lecture-Gupta</i>	0.787	0.987	0.970	0.939	0.919	0.887	0.904	0.856	0.899	0.907	0.884	0.880
	<i>Lecture-Gupta</i>		1.144	1.183	1.219	1.138	0.973	0.999	0.989	0.883	0.900	1.189	1.066
	<i>Lecture-Reisslein</i>	0.870	0.966	0.958	0.940	0.922	0.926	0.904	0.955	0.960	0.889	0.960	0.981
	<i>Lecture-Reisslein</i>		1.173	1.179	1.180	1.165	1.119	1.101	1.138	1.171	1.178	1.215	1.254
QCIF	<i>Jurassic Park I</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.	<i>Jurassic Park I</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.	<i>Star Wars IV</i>	0.848	0.824	0.823	0.799	0.797	0.827	0.845	0.836	0.848	0.855	0.862	0.870
	<i>Star Wars IV</i>		0.967	0.990	0.980	0.975	0.940	0.894	0.865	0.855	0.878	0.894	0.868
	<i>The Firm</i>	0.886	0.875	0.856	0.834	0.822	0.821	0.841	0.810	0.778	0.774	0.734	0.721
	<i>The Firm</i>		0.966	1.023	1.030	1.							

Table 3: continued

Enc. M.	Video	Aggregation level $\alpha$ [frames]											
		1	12	24	48	96	192	300	396	504	600	696	792
L.Q. No R.C.	<i>Citizen Kane</i>		1.012	1.035	1.042	0.985	0.899	0.852	0.827	0.840	0.853	0.846	0.874
	<i>Die Hard I</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
	<i>Die Hard I</i>		1.024	1.050	0.988	0.950	0.898	0.834	0.947	0.837	0.735	0.780	0.793
	<i>Jurassic Park I</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
	<i>Jurassic Park I</i>		1.041	1.109	1.030	0.950	0.923	0.892	0.871	0.875	0.829	0.776	0.795
	<i>Silence of the Lambs</i>	0.871	0.892	0.878	0.876	0.887	0.881	0.842	0.883	0.852	0.820	0.825	0.856
	<i>Silence of the Lambs</i>		0.995	1.072	1.036	0.984	0.942	0.966	0.916	0.906	0.971	0.980	1.039
	<i>Star Wars IV</i>	0.845	0.810	0.811	0.787	0.786	0.815	0.836	0.832	0.834	0.868	0.872	0.864
	<i>Star Wars IV</i>		0.959	0.982	0.971	0.979	0.931	0.874	0.848	0.832	0.865	0.890	0.831
	<i>Star Wars V</i>	0.863	0.848	0.831	0.827	0.837	0.823	0.826	0.859	0.909	0.877	0.965	0.946
	<i>Star Wars V</i>		1.048	1.046	0.993	0.916	0.906	0.857	0.809	0.802	0.780	0.778	0.773
	<i>The Firm</i>	0.872	0.869	0.852	0.829	0.823	0.816	0.843	0.802	0.758	0.762	0.723	0.719
	<i>The Firm</i>		0.946	0.998	1.010	0.971	0.961	0.891	1.008	0.936	1.038	0.955	0.964
	<i>Terminator I</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
	<i>Terminator I</i>		1.005	1.042	1.017	1.013	0.988	1.010	1.004	0.992	0.994	1.029	0.980
	<i>Total Recall</i>	0.861	0.834	0.805	0.795	0.768	0.746	0.739	0.728	0.720	0.735	0.750	0.666
	<i>Total Recall</i>		0.988	1.013	0.998	0.969	0.985	1.023	0.984	0.872	0.955	0.939	1.002
	<i>Aladdin</i>	0.856	0.857	0.849	0.856	0.870	0.879	0.901	0.823	0.880	0.826	0.795	0.767
	<i>Aladdin</i>		0.956	0.936	0.913	0.879	0.942	0.898	0.922	1.001	0.996	0.946	1.040
	<i>Cinderella</i>	0.815	0.784	0.766	0.775	0.765	0.772	0.749	0.722	0.704	0.696	0.687	0.724
	<i>Cinderella</i>		0.969	0.963	0.921	0.901	0.896	0.935	0.901	0.964	0.964	0.940	0.889
	<i>Baseball with Comm</i>	0.812	0.761	0.737	0.682	0.664	0.665	0.707	0.708	0.702	0.737	0.770	0.746
	<i>Baseball with Comm</i>		1.005	0.996	0.979	0.912	0.803	0.756	0.729	0.751	0.690	0.726	0.734
	<i>Snowboard with Comm</i>	0.813	0.763	0.729	0.694	0.648	0.612	0.565	0.597	0.595	0.582	0.544	0.545
	<i>Snowboard with Comm</i>		1.010	0.980	0.898	0.881	0.788	0.708	0.658	0.653	0.602	0.611	0.662
	<i>Oprah w/o Comm</i>	0.844	0.860	0.836	0.800	0.782	0.769	0.737	0.668	0.650	0.702	0.681	0.599
	<i>Oprah w/o Comm</i>		0.960	0.990	1.005	0.993	0.967	0.940	1.022	0.968	0.993	0.895	1.022
	<i>Tonight Show w/o Comm</i>	0.776	0.837	0.838	0.850	0.879	0.848	0.894	0.878	0.930	0.929	0.877	0.952
	<i>Tonight Show w/o Comm</i>		1.013	1.053	1.065	1.111	1.076	1.054	1.176	1.189	1.183	1.228	1.234
	<i>Lecture-Gupta</i>	0.737	0.969	0.949	0.928	0.894	0.871	0.854	0.799	0.834	0.825	0.832	0.787
	<i>Lecture-Gupta</i>		1.029	1.071	1.142	1.035	0.875	0.967	0.960	0.881	0.867	1.088	0.962
	<i>Lecture-Reisslein</i>	0.828	0.941	0.945	0.940	0.926	0.944	0.937	0.961	0.964	0.936	0.945	0.981
	<i>Lecture-Reisslein</i>		1.085	1.080	1.130	1.083	1.076	1.077	1.114	1.142	1.130	1.281	1.222
QCIF R.C. 64 kbps	<i>Citizen Kane</i>	0.654	0.724	0.735	0.747	0.732	0.704	0.675	0.696	0.708	0.638	0.625	0.647
	<i>Citizen Kane</i>		0.874	0.903	0.900	0.890	0.831	0.752	0.791	0.832	0.751	0.744	0.771
	<i>Die Hard I</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
	<i>Die Hard I</i>		1.017	1.044	0.976	0.936	0.900	0.839	0.948	0.834	0.724	0.776	0.805
	<i>Jurassic Park I</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
	<i>Jurassic Park I</i>		1.025	1.081	1.009	0.947	0.883	0.870	0.840	0.839	0.842	0.731	0.821
	<i>Silence of the Lambs</i>	0.661	0.682	0.661	0.643	0.645	0.632	0.659	0.618	0.659	0.654	0.591	0.583
	<i>Silence of the Lambs</i>		0.890	0.911	0.917	0.877	0.867	0.872	0.799	0.799	0.863	0.926	1.005
	<i>Star Wars IV</i>	0.709	0.657	0.656	0.624	0.616	0.631	0.625	0.635	0.674	0.659	0.563	0.640
	<i>Star Wars IV</i>		0.871	0.900	0.872	0.869	0.834	0.831	0.773	0.773	0.792	0.810	0.793
	<i>Star Wars V</i>	0.814	0.833	0.826	0.810	0.850	0.850	0.835	0.867	0.908	0.876	0.963	0.917
	<i>Star Wars V</i>		0.971	0.967	0.931	0.882	0.859	0.854	0.855	0.828	0.844	0.860	0.835
	<i>The Firm</i>	0.724	0.742	0.720	0.697	0.685	0.654	0.648	0.606	0.580	0.555	0.506	0.485
	<i>The Firm</i>		0.857	0.915	0.951	0.893	0.900	0.805	0.881	0.808	0.848	0.808	0.810
	<i>Terminator I</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
	<i>Terminator I</i>		0.977	1.004	0.992	0.995	0.973	1.012	0.971	0.981	0.977	1.075	0.998
	<i>Total Recall</i>	0.839	0.819	0.793	0.795	0.770	0.739	0.732	0.716	0.709	0.710	0.714	0.635
	<i>Total Recall</i>		0.966	0.992	0.996	0.982	0.966	0.979	0.921	0.850	0.905	0.927	1.062
	<i>Aladdin</i>	0.848	0.860	0.850	0.858	0.874	0.880	0.900	0.822	0.880	0.822	0.797	0.770
	<i>Aladdin</i>		0.946	0.924	0.901	0.875	0.922	0.891	0.910	0.970	0.971	0.940	1.069
	<i>Cinderella</i>	0.808	0.776	0.756	0.760	0.748	0.756	0.746	0.715	0.697	0.697	0.688	0.728
	<i>Cinderella</i>		0.944	0.928	0.909	0.893	0.875	0.907	0.875	0.957	0.942	0.911	0.902
	<i>Baseball with Comm</i>	0.809	0.776	0.755	0.692	0.669	0.665	0.716	0.715	0.712	0.757	0.785	0.771
	<i>Baseball with Comm</i>		1.002	0.995	0.970	0.900	0.801	0.763	0.755	0.782	0.770	0.731	0.781
	<i>Snowboard with Comm</i>	0.812	0.765	0.732	0.698	0.650	0.616	0.566	0.603	0.598	0.584	0.550	0.558
	<i>Snowboard with Comm</i>		1.005	0.983	0.896	0.881	0.787	0.703	0.656	0.647	0.591	0.598	0.652
	<i>Oprah w/o Comm</i>	0.832	0.844	0.826	0.789	0.775	0.768	0.738	0.670	0.644	0.697	0.674	0.588
	<i>Oprah w/o Comm</i>		0.950	0.952	0.961	0.941	0.918	0.913	0.934	0.905	0.969	0.872	0.997
	<i>Tonight Show w/o Comm</i>	0.662	0.770	0.781	0.800	0.790	0.795	0.784	0.794	0.762	0.760	0.797	0.814
	<i>Tonight Show w/o Comm</i>		0.895	0.985	1.069	1.100	1.088	1.035	1.082	0.898	1.113	1.009	0.803
	<i>Lecture-Gupta</i>	0.734	0.941	0.934	0.925	0.897	0.850	0.838	0.800	0.829	0.832	0.820	0.775
	<i>Lecture-Gupta</i>		1.015	1.063	1.118	1.015	0.870	0.961	0.976	0.866	0.879	1.084	0.961
	<i>Lecture-Reisslein</i>	0.827	0.936	0.937	0.924	0.919	0.947	0.933	0.954	0.948	0.918	0.955	0.969
<i>Lecture-Reisslein</i>		1.010	1.037	1.115	1.075	1.074	1.074	1.048	1.049	1.060	1.177	1.133	
QCIF R.C. 128 kbps	<i>Citizen Kane</i>	0.225	0.411	0.445	0.453	0.420	0.390	0.414	0.463	0.485	0.431	0.434	0.553
	<i>Citizen Kane</i>		0.569	0.539	0.527	0.391	0.113	-0.117	-0.143	-0.030	-0.142	-0.168	-0.087
	<i>Die Hard I</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
	<i>Die Hard I</i>		0.585	0.542	0.522	0.383	0.118	-0.047	-0.052	-0.109	-0.203	-0.160	-0.305
	<i>Jurassic Park I</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
	<i>Jurassic Park I</i>		0.697	0.746	0.822	0.862	1.029	0.686	0.476	0.252	0.336	0.001	-0.039
	<i>Silence of the Lambs</i>	0.258	0.433	0.436	0.428	0.421	0.503	0.523	0.594	0.553	0.566	0.487	0.599
	<i>Silence of the Lambs</i>		0.723	0.835	0.972	1.039	0.951	0.631	0.329	0.198	0.127	-0.032	0.004
	<i>Star Wars IV</i>	0.251	0.385	0.399	0.428	0.393	0.401	0.438	0.474	0.461	0.431	0.488	0.502
	<i>Star Wars IV</i>		0.388	0.309	0.224	0.068	0.074	-0.029	0.316	0.004	-0.105	0.073	0.581
	<i>Star Wars V</i>	0.307	0.397	0.399	0.351	0.388	0.397	0.393	0.381	0.450	0.400	0.398	0.433
	<i>Star Wars V</i>		0.524	0.401	0.266	0.199	0.069	0.077	-0.004	-0.313	0.025	-0.089	-0.158
	<i>The Firm</i>	0.284	0.445	0.432	0.458	0.446	0.428	0.493	0.491	0.508	0.519	0.547	0.500
	<i>The Firm</i>		0.547	0.473	0.360	0.218	-0.066	-0.149	-0.152	-0.152	-0.079	-0.187	

Table 3: continued

Enc. M.	Video	Aggregation level $a$ [frames]											
		1	12	24	48	96	192	300	396	504	600	696	792
	<i>Total Recall</i>		0.459	0.363	0.267	0.072	-0.002	-0.244	-0.080	-0.146	-0.169	-0.162	-0.096
	<i>Aladdin</i>	0.524	0.556	0.538	0.532	0.520	0.499	0.548	0.438	0.515	0.521	0.485	0.487
	<i>Aladdin</i>		0.739	0.695	0.668	0.720	0.721	0.674	0.766	0.657	0.655	0.752	0.773
	<i>Cinderella</i>	0.430	0.531	0.516	0.487	0.485	0.455	0.435	0.413	0.413	0.443	0.517	0.386
	<i>Cinderella</i>		0.712	0.679	0.661	0.611	0.369	0.157	0.143	-0.022	-0.018	-0.060	-0.012
	<i>Baseball with Comm</i>	0.368	0.426	0.414	0.376	0.392	0.400	0.354	0.390	0.451	0.434	0.422	0.366
	<i>Baseball with Comm</i>		0.595	0.493	0.388	0.457	0.180	0.044	0.042	-0.131	-0.307	-0.048	-0.267
	<i>Snowboard with Comm</i>	0.496	0.535	0.530	0.509	0.485	0.465	0.438	0.440	0.458	0.437	0.379	0.440
	<i>Snowboard with Comm</i>		0.747	0.655	0.569	0.462	0.367	0.278	0.098	0.003	-0.007	-0.075	-0.144
	<i>Oprah w/o Comm</i>	0.302	0.484	0.462	0.465	0.451	0.484	0.452	0.464	0.470	0.459	0.448	0.469
	<i>Oprah w/o Comm</i>		0.567	0.523	0.418	0.172	-0.060	-0.174	-0.136	-0.084	-0.213	-0.190	-0.106
	<i>Tonight Show w/o Comm</i>	0.324	0.514	0.513	0.529	0.459	0.434	0.412	0.537	0.284	0.394	0.423	0.417
	<i>Tonight Show w/o Comm</i>		0.654	0.677	0.567	0.342	0.003	-0.089	-0.203	-0.059	-0.133	-0.122	-0.205
	<i>Lecture-Gupta</i>	0.216	0.414	0.402	0.396	0.414	0.466	0.547	0.644	0.706	0.664	0.616	0.551
	<i>Lecture-Gupta</i>		0.676	0.607	0.764	0.857	0.892	0.376	0.438	0.110	0.287	-0.004	-0.128
	<i>Lecture-Reisslein</i>	0.309	0.551	0.553	0.539	0.483	0.469	0.439	0.473	0.510	0.504	0.409	0.557
	<i>Lecture-Reisslein</i>		0.816	0.739	0.631	0.344	0.042	-0.108	-0.108	-0.115	-0.233	-0.156	-0.161
QCIF	<i>Citizen Kane</i>	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.	<i>Citizen Kane</i>		0.016	-0.044	-0.123	-0.142	-0.104	0.006	0.055	-0.041	0.114	0.138	0.094
256 kbps	<i>Die Hard I</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
	<i>Die Hard I</i>		-0.057	-0.132	-0.114	-0.119	-0.088	0.011	0.147	0.088	0.175	0.122	0.213
	<i>Jurassic Park I</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
	<i>Jurassic Park I</i>		0.008	-0.077	-0.087	-0.102	-0.078	-0.012	0.053	0.140	0.127	-0.040	0.228
	<i>Silence of the Lambs</i>	0.182	0.324	0.345	0.349	0.352	0.372	0.362	0.404	0.671	0.711	0.995	0.799
	<i>Silence of the Lambs</i>		0.365	0.416	0.379	-0.093	-0.132	0.011	0.014	-0.257	0.093	0.329	0.202
	<i>Star Wars IV</i>	0.180	0.316	0.256	0.273	0.265	0.343	0.263	0.509	0.509	0.459	1.082	0.882
	<i>Star Wars IV</i>		0.162	-0.057	-0.091	-0.054	0.019	0.029	-0.048	0.066	0.081	0.194	0.155
	<i>Star Wars V</i>	0.167	0.257	0.289	0.303	0.287	0.307	0.324	0.397	0.463	0.574	0.636	0.579
	<i>Star Wars V</i>		0.013	-0.069	-0.104	-0.048	0.022	0.044	-0.056	0.052	0.262	0.073	-0.080
	<i>The Firm</i>	0.169	0.272	0.264	0.263	0.303	0.363	0.321	0.384	0.473	0.442	0.721	0.958
	<i>The Firm</i>		-0.033	-0.122	-0.157	-0.109	-0.041	0.017	0.076	0.092	0.175	0.025	0.181
	<i>Terminator I</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
	<i>Terminator I</i>		0.346	0.241	0.075	0.012	-0.061	0.097	-0.026	-0.072	-0.037	0.172	-0.107
	<i>Total Recall</i>	0.168	0.286	0.240	0.253	0.269	0.307	0.403	0.381	0.386	0.494	0.612	0.910
	<i>Total Recall</i>		-0.039	-0.147	-0.138	-0.014	0.028	0.038	-0.037	0.022	0.080	0.119	0.269
	<i>Aladdin</i>	0.220	0.331	0.322	0.335	0.377	0.401	0.379	0.412	0.353	0.352	0.560	0.489
	<i>Aladdin</i>		0.209	-0.027	-0.146	-0.189	-0.160	-0.183	-0.062	-0.205	-0.025	0.054	-0.176
	<i>Cinderella</i>	0.271	0.449	0.456	0.439	0.448	0.462	0.275	0.426	0.455	0.456	0.527	0.604
	<i>Cinderella</i>		0.603	0.525	0.221	-0.085	-0.174	-0.058	-0.199	-0.232	0.067	0.075	-0.272
	<i>Baseball with Comm</i>	0.182	0.308	0.306	0.300	0.289	0.276	0.416	0.381	0.570	0.520	0.601	0.693
	<i>Baseball with Comm</i>		0.034	-0.079	-0.117	-0.081	-0.001	-0.079	-0.074	0.047	0.155	0.047	0.046
	<i>Snowboard with Comm</i>	0.251	0.366	0.353	0.392	0.366	0.416	0.342	0.392	0.330	0.408	0.543	0.699
	<i>Snowboard with Comm</i>		0.273	0.075	-0.096	-0.141	-0.125	-0.031	0.023	-0.035	-0.123	0.079	-0.142
	<i>Oprah w/o Comm</i>	0.131	0.307	0.307	0.237	0.300	0.294	0.359	0.460	0.458	0.605	1.047	0.471
	<i>Oprah w/o Comm</i>		0.049	-0.050	-0.054	-0.015	0.044	0.045	-0.067	0.351	0.068	0.224	0.171
	<i>Tonight Show w/o Comm</i>	0.143	0.271	0.301	0.291	0.319	0.314	0.423	0.380	0.462	0.562	0.372	0.614
	<i>Tonight Show w/o Comm</i>		-0.020	-0.114	-0.121	-0.140	-0.005	-0.048	0.062	0.273	0.162	-0.038	0.110
	<i>Lecture-Gupta</i>	0.119	0.169	0.166	0.190	0.188	0.156	0.287	0.317	0.353	0.504	0.767	0.648
	<i>Lecture-Gupta</i>		-0.025	-0.128	-0.138	-0.070	-0.038	-0.061	0.107	-0.029	0.072	0.117	0.133
	<i>Lecture-Reisslein</i>	0.123	0.243	0.230	0.250	0.232	0.272	0.370	0.378	0.518	0.669	0.663	1.037
	<i>Lecture-Reisslein</i>		0.009	-0.045	-0.093	-0.045	0.040	0.110	0.112	0.246	0.255	0.257	0.063
CIF	<i>Silence of the Lambs</i>	0.990	0.929	0.904	0.913	0.932	0.959	0.922	0.925	0.821	0.850	0.893	0.805
H.Q.	<i>Silence of the Lambs</i>		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.													
CIF	<i>Silence of the Lambs</i>	0.899	0.922	0.906	0.906	0.906	0.894	0.844	0.872	0.753	0.760	0.878	0.807
M.Q.	<i>Silence of the Lambs</i>		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.													
CIF	<i>Silence of the Lambs</i>	0.899	0.908	0.894	0.891	0.873	0.856	0.813	0.856	0.738	0.738	0.821	0.782
L.Q.	<i>Silence of the Lambs</i>		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.													
CIF	<i>Silence of the Lambs</i>	0.893	0.904	0.887	0.874	0.865	0.851	0.818	0.859	0.730	0.745	0.846	0.770
R.C.	<i>Silence of the Lambs</i>		0.973	1.062	1.039	1.007	0.984	0.981	0.894	0.876	0.876	1.034	0.960
64 kbps													
CIF	<i>Silence of the Lambs</i>	0.896	0.904	0.888	0.874	0.866	0.851	0.817	0.860	0.730	0.746	0.847	0.770
R.C.	<i>Silence of the Lambs</i>		0.973	1.062	1.039	1.007	0.982	0.983	0.894	0.876	0.877	1.037	0.959
128 kbps													
CIF	<i>Silence of the Lambs</i>	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.	<i>Silence of the Lambs</i>		0.902	0.945	0.923	0.913	0.889	0.952	0.815	0.824	0.791	0.809	0.906
256 kbps													

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 .

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

Table 4: *continued*

Enc. M.	Video	VT	Logscale Diagram		
		$H$	$\underline{c}_f$	$\alpha$	$H$
	<i>Tonight Show w/o Comm</i>	0.943	1.025	0.628	0.814
QCIF	<i>Citizen Kane</i>	0.844	0.006	1.115	1.058
L.Q.	<i>Die Hard I</i>	0.722	0.047	0.841	0.920
No R.C.	<i>Jurassic Park I</i>	0.628	0.003	1.281	1.141
	<i>Silence of the Lambs</i>	0.866	1.092	0.318	0.659
	<i>Star Wars IV</i>	0.773	0.019	0.940	0.970
	<i>Star Wars V</i>	0.756	0.048	0.811	0.905
	<i>The Firm</i>	0.821	0.057	0.743	0.871
	<i>Terminator I</i>	0.845	0.029	0.900	0.950
	<i>Total Recall</i>	0.706	0.010	1.082	1.041
	<i>Aladdin</i>	0.859	0.046	0.836	0.918
	<i>Cinderella</i>	0.775	0.081	0.759	0.880
	<i>Baseball with Comm</i>	0.586	0.274	0.569	0.784
	<i>Snowboard with Comm</i>	0.580	1.587	0.223	0.612
	<i>Oprah w/o Comm</i>	0.780	0.007	1.056	1.028
	<i>Tonight Show w/o Comm</i>	0.936	0.000	1.793	1.397
	<i>Lecture-Gupta</i>	0.729	0.002	0.932	0.966
	<i>Lecture-Reisslein</i>	0.948	0.002	1.108	1.054
QCIF	<i>Citizen Kane</i>	0.666	1.185	0.081	0.541
R.C.	<i>Die Hard I</i>	0.719	0.048	0.836	0.918
64 kbps	<i>Jurassic Park I</i>	0.625	0.016	0.982	0.991
	<i>Silence of the Lambs</i>	0.763	23827.756	-1.170	-0.085
	<i>Star Wars IV</i>	0.735	11.513	-0.218	0.391
	<i>Star Wars V</i>	0.728	0.153	0.585	0.792
	<i>The Firm</i>	0.714	0.017	0.857	0.929
	<i>Terminator I</i>	0.837	0.031	0.874	0.937
	<i>Total Recall</i>	0.680	0.011	0.992	0.996
	<i>Aladdin</i>	0.857	0.046	0.835	0.917
	<i>Cinderella</i>	0.763	0.082	0.753	0.876
	<i>Baseball with Comm</i>	0.575	0.302	0.547	0.774
	<i>Snowboard with Comm</i>	0.583	1.355	0.243	0.621
	<i>Oprah w/o Comm</i>	0.775	0.013	0.917	0.959
	<i>Tonight Show w/o Comm</i>	0.773	0.000	1.182	1.091
	<i>Lecture-Gupta</i>	0.724	0.003	0.918	0.959
	<i>Lecture-Reisslein</i>	0.932	0.002	1.106	1.053
QCIF	<i>Citizen Kane</i>	-0.282	25406.062	-2.233	-0.616
R.C.	<i>Die Hard I</i>	-0.293	16539.776	-1.872	-0.436
128 kbps	<i>Jurassic Park I</i>	-0.540	2521.243	-1.169	-0.084
	<i>Silence of the Lambs</i>	-0.748	0.359	-1.249	-0.124
	<i>Star Wars IV</i>	-0.049	24.640	-1.694	-0.347
	<i>Star Wars V</i>	-0.124	511.025	-1.884	-0.442
	<i>The Firm</i>	-0.678	2140557.017	-2.966	-0.983
	<i>Terminator I</i>	-0.078	111350.456	-1.829	-0.415
	<i>Total Recall</i>	-0.071	650.269	-1.709	-0.355
	<i>Aladdin</i>	0.476	1655151012.080	-2.662	-0.831
	<i>Cinderella</i>	-0.522	1677.828	-1.267	-0.134
	<i>Baseball with Comm</i>	0.300	38736466387941.400	-4.603	-1.802
	<i>Snowboard with Comm</i>	0.088	65.610	-0.685	0.157
	<i>Oprah w/o Comm</i>	0.062	13008691.086	-3.022	-1.011
	<i>Tonight Show w/o Comm</i>	-0.227	7328.228	-1.825	-0.413
	<i>Lecture-Gupta</i>	-1.154	8.860	-1.513	-0.257
	<i>Lecture-Reisslein</i>	-0.695	1192.844	-1.525	-0.263
QCIF	<i>Citizen Kane</i>	0.054	2.514	-1.288	-0.144
R.C.	<i>Die Hard I</i>	0.020	0.624	-1.081	-0.041
256 kbps	<i>Jurassic Park I</i>	0.075	1.815	-1.254	-0.127
	<i>Silence of the Lambs</i>	-0.190	389.806	-1.917	-0.458
	<i>Star Wars IV</i>	0.076	2.776	-1.314	-0.157
	<i>Star Wars V</i>	-0.027	3.727	-1.365	-0.183
	<i>The Firm</i>	0.046	2.823	-1.299	-0.150
	<i>Terminator I</i>	0.165	4.609	-1.304	-0.152



Table 4: *continued*

Enc. M.	Video	VT $H$	Logscale Diagram		
			$\underline{c}_f$	$\alpha$	$H$
	<i>Total Recall</i>	0.032	3.094	-1.301	-0.151
	<i>Aladdin</i>	0.053	78.487	-1.767	-0.384
	<i>Cinderella</i>	-0.284	5.941	-1.392	-0.196
	<i>Baseball with Comm</i>	-0.012	6.620	-1.432	-0.216
	<i>Snowboard with Comm</i>	-0.051	20.291	-1.485	-0.243
	<i>Oprah w/o Comm</i>	0.104	1.364	-1.266	-0.133
	<i>Tonight Show w/o Comm</i>	0.186	11.832	-1.580	-0.290
	<i>Lecture-Gupta</i>	0.126	0.032	-1.017	-0.008
	<i>Lecture-Reisslein</i>	0.042	0.058	-0.924	0.038
CIF H.Q. No.R.C.	<i>Silence of the Lambs</i>	0.908	0.000	2.205	1.603
CIF M.Q. No.R.C.	<i>Silence of the Lambs</i>	0.869	0.000	1.869	1.434
CIF L.Q. No R.C.	<i>Silence of the Lambs</i>	0.838	0.030	0.966	0.983
CIF R.C. 64 kbps	<i>Silence of the Lambs</i>	0.841	0.033	0.955	0.977
CIF R.C. 128 kbps	<i>Silence of the Lambs</i>	0.841	0.033	0.955	0.977
CIF R.C. 256 kbps	<i>Silence of the Lambs</i>	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							
		$q = 0.5$	$q = 1$	$q = 1.5$	$q = 2$	$q = 2.5$	$q = 3$	$q = 3.5$	$q = 4$
Q CIF	<i>Citizen Kane</i>	0.524	0.999	1.421	1.801	2.147	2.469	2.772	3.060
H.Q.	<i>Die Hard I</i>	0.415	0.818	1.208	1.582	1.940	2.282	2.608	2.921
No.R.C.	<i>Jurassic Park I</i>	0.547	1.070	1.581	2.095	2.614	3.131	3.639	4.139
	<i>Silence of the Lambs</i>	0.535	1.033	1.518	1.998	2.473	2.945	3.414	3.879
	<i>Star Wars IV</i>	0.425	0.825	1.207	1.574	1.929	2.274	2.611	2.942
	<i>Star Wars V</i>	0.503	1.001	1.487	1.961	2.424	2.877	3.322	3.758
	<i>The Firm</i>	0.549	1.097	1.636	2.160	2.666	3.154	3.627	4.092
	<i>Terminator I</i>	0.510	0.991	1.455	1.905	2.344	2.775	3.199	3.618
	<i>Total Recall</i>	0.521	1.016	1.489	1.942	2.377	2.794	3.196	3.583
	<i>Aladdin</i>	0.535	1.061	1.574	2.073	2.558	3.028	3.486	3.926
	<i>Cinderella</i>	0.485	0.938	1.360	1.752	2.115	2.453	2.772	3.080

Table 5: *continued*

Enc. M.	Video	Multiscale Diagram, $\alpha_q$ for							
		$q = 0.5$	$q = 1$	$q = 1.5$	$q = 2$	$q = 2.5$	$q = 3$	$q = 3.5$	$q = 4$
	<i>Baseball with Comm</i>	0.406	0.798	1.178	1.545	1.906	2.261	2.616	2.970
	<i>Snowboard with Comm</i>	0.250	0.538	0.840	1.142	1.439	1.728	2.008	2.280
	<i>Oprah w/o Comm</i>	0.473	0.935	1.394	1.858	2.322	2.783	3.235	3.675
	<i>Tonight Show w/o Comm</i>	0.551	1.063	1.554	2.020	2.463	2.887	3.296	3.695
	<i>Lecture-Gupta</i>	0.673	1.187	1.609	1.987	2.343	2.687	3.025	3.361
	<i>Lecture-Reisslein</i>	0.692	1.310	1.840	2.294	2.700	3.079	3.446	3.807
QCIF	<i>Jurassic Park I</i>	0.581	1.158	1.736	2.316	2.891	3.453	3.998	4.538
H.-M.Q.	<i>Star Wars IV</i>	0.503	1.002	1.488	1.952	2.390	2.800	3.149	3.523
No.R.C.	<i>The Firm</i>	0.590	1.188	1.791	2.397	3.000	3.596	4.182	4.760
	<i>Tonight Show w/o Comm</i>	0.542	1.045	1.506	1.933	2.329	2.702	3.059	3.404
QCIF	<i>Citizen Kane</i>	0.515	0.968	1.367	1.717	2.027	2.304	2.556	2.789
M.Q.	<i>Die Hard I</i>	0.518	1.037	1.557	2.080	2.611	3.132	3.648	4.159
No.R.C.	<i>Jurassic Park I</i>	0.544	1.068	1.597	2.140	2.685	3.218	3.732	4.231
	<i>Silence of the Lambs</i>	0.548	1.092	1.621	2.136	2.622	3.085	3.536	3.980
	<i>Star Wars IV</i>	0.503	1.006	1.501	1.977	2.424	2.798	3.176	3.540
	<i>Star Wars V</i>	0.519	1.007	1.470	1.916	2.347	2.767	3.177	3.580
	<i>The Firm</i>	0.532	1.061	1.573	2.061	2.523	2.961	3.381	3.788
	<i>Terminator I</i>	0.516	1.001	1.460	1.896	2.314	2.718	3.112	3.498
	<i>Total Recall</i>	0.548	1.082	1.599	2.096	2.577	3.044	3.494	3.936
	<i>Aladdin</i>	0.500	0.989	1.461	1.917	2.357	2.783	3.195	3.598
	<i>Cinderella</i>	0.483	0.938	1.353	1.719	2.041	2.329	2.599	2.859
	<i>Baseball with Comm</i>	0.547	1.074	1.578	2.053	2.505	2.946	3.377	3.794
	<i>Snowboard with Comm</i>	0.292	0.593	0.888	1.167	1.427	1.667	1.890	2.100
	<i>Oprah w/o Comm</i>	0.511	0.986	1.437	1.874	2.299	2.714	3.118	3.512
	<i>Tonight Show w/o Comm</i>	0.545	1.042	1.500	1.920	2.307	2.669	3.015	3.349
	<i>Lecture-Gupta</i>	0.526	1.131	1.749	2.343	2.901	3.430	3.938	4.433
	<i>Lecture-Reisslein</i>	0.625	1.263	1.895	2.516	3.123	3.726	4.370	4.970
QCIF	<i>Jurassic Park I</i>	0.555	1.081	1.600	2.128	2.659	3.188	3.696	4.189
M.-L.Q.	<i>Star Wars IV</i>	0.395	0.761	1.104	1.430	1.741	2.040	2.329	2.609
No R.C.	<i>The Firm</i>	0.506	0.991	1.462	1.919	2.357	2.775	3.174	3.557
	<i>Tonight Show w/o Comm</i>	0.538	1.043	1.516	1.954	2.360	2.742	3.108	3.462
QCIF	<i>Citizen Kane</i>	0.535	1.075	1.611	2.135	2.645	3.140	3.625	4.104
L.Q.	<i>Die Hard I</i>	0.477	0.933	1.378	1.819	2.263	2.712	3.165	3.620
No.R.C.	<i>Jurassic Park I</i>	0.570	1.133	1.691	2.245	2.797	3.341	3.875	4.391
	<i>Silence of the Lambs</i>	0.455	0.826	1.094	1.243	1.290	1.270	1.214	1.143
	<i>Star Wars IV</i>	0.500	0.995	1.476	1.940	2.383	2.801	3.166	3.552
	<i>Star Wars V</i>	0.462	0.913	1.350	1.775	2.191	2.600	3.003	3.401
	<i>The Firm</i>	0.469	0.913	1.335	1.737	2.120	2.488	2.842	3.188
	<i>Terminator I</i>	0.507	0.989	1.452	1.899	2.332	2.751	3.158	3.554
	<i>Total Recall</i>	0.536	1.061	1.574	2.071	2.550	3.015	3.457	3.888
	<i>Aladdin</i>	0.477	0.945	1.400	1.844	2.275	2.695	3.105	3.508
	<i>Cinderella</i>	0.473	0.935	1.389	1.833	2.266	2.687	3.095	3.495
	<i>Baseball with Comm</i>	0.380	0.762	1.147	1.533	1.917	2.294	2.663	3.019
	<i>Snowboard with Comm</i>	0.308	0.614	0.917	1.213	1.495	1.760	2.006	2.235
	<i>Oprah w/o Comm</i>	0.494	1.011	1.542	2.081	2.618	3.144	3.660	4.155
	<i>Tonight Show w/o Comm</i>	0.789	1.527	2.250	2.923	3.535	4.094	4.612	5.103
	<i>Lecture-Gupta</i>	0.474	1.005	1.541	2.060	2.553	3.023	3.475	3.914
	<i>Lecture-Reisslein</i>	0.568	1.138	1.700	2.257	2.803	3.386	3.942	4.494
QCIF	<i>Citizen Kane</i>	0.365	0.615	0.851	1.078	1.292	1.496	1.692	1.883
R.C.	<i>Die Hard I</i>	0.484	0.939	1.378	1.813	2.252	2.696	3.145	3.597
64 kbps	<i>Jurassic Park I</i>	0.488	0.965	1.456	1.965	2.479	2.984	3.474	3.948
	<i>Silence of the Lambs</i>	0.083	-0.067	-0.266	-0.466	-0.662	-0.853	-1.041	-1.227
	<i>Star Wars IV</i>	0.194	0.388	0.606	0.826	1.036	1.231	1.411	1.577
	<i>Star Wars V</i>	0.414	0.817	1.183	1.508	1.791	2.062	2.321	2.560
	<i>The Firm</i>	0.472	0.959	1.422	1.840	2.221	2.583	2.931	3.288
	<i>Terminator I</i>	0.503	0.982	1.440	1.882	2.310	2.723	3.123	3.512
	<i>Total Recall</i>	0.495	0.990	1.476	1.951	2.406	2.839	3.248	3.637
	<i>Aladdin</i>	0.483	0.953	1.405	1.836	2.243	2.628	2.996	3.350
	<i>Cinderella</i>	0.467	0.929	1.386	1.834	2.271	2.696	3.108	3.510
	<i>Baseball with Comm</i>	0.381	0.755	1.133	1.512	1.890	2.262	2.623	2.973

Table 5: *continued*

Enc. M.	Video	Multiscale Diagram, $\alpha_q$ for							
		$q = 0.5$	$q = 1$	$q = 1.5$	$q = 2$	$q = 2.5$	$q = 3$	$q = 3.5$	$q = 4$
	<i>Snowboard with Comm</i>	0.313	0.620	0.923	1.219	1.502	1.767	2.013	2.243
	<i>Oprah w/o Comm</i>	0.503	0.992	1.457	1.905	2.339	2.762	3.179	3.591
	<i>Tonight Show w/o Comm</i>	0.844	1.531	2.110	2.588	2.998	3.367	3.715	4.048
	<i>Lecture-Gupta</i>	0.482	1.001	1.507	1.978	2.411	2.817	3.206	3.584
	<i>Lecture-Reisslein</i>	0.557	1.126	1.704	2.289	2.880	3.473	4.003	4.569
Q CIF	<i>Citizen Kane</i>	-0.040	-0.256	-0.621	-1.035	-1.453	-1.868	-2.281	-2.695
R.C.	<i>Die Hard I</i>	0.047	-0.103	-0.453	-0.899	-1.379	-1.872	-2.369	-2.867
128 kbps	<i>Jurassic Park I</i>	0.401	0.335	0.131	-0.087	-0.312	-0.546	-0.786	-1.033
	<i>Silence of the Lambs</i>	-0.077	-0.229	-0.557	-1.091	-1.739	-2.429	-3.126	-3.820
	<i>Star Wars IV</i>	-0.165	-0.367	-0.595	-0.844	-1.107	-1.382	-1.666	-1.959
	<i>Star Wars V</i>	-0.152	-0.460	-0.848	-1.282	-1.746	-2.229	-2.726	-3.233
	<i>The Firm</i>	-0.154	-0.450	-1.007	-1.751	-2.560	-3.375	-4.182	-4.982
	<i>Terminator I</i>	0.173	0.020	-0.342	-0.761	-1.193	-1.626	-2.059	-2.488
	<i>Total Recall</i>	0.017	-0.057	-0.336	-0.788	-1.297	-1.811	-2.320	-2.825
	<i>Aladdin</i>	-0.040	0.106	0.235	0.254	0.190	0.074	-0.072	-0.235
	<i>Cinderella</i>	0.143	0.106	-0.091	-0.339	-0.600	-0.866	-1.138	-1.414
	<i>Baseball with Comm</i>	-0.300	-1.167	-2.305	-3.477	-4.632	-5.779	-6.925	-8.075
	<i>Snowboard with Comm</i>	0.166	0.250	0.284	0.294	0.287	0.263	0.224	0.173
	<i>Oprah w/o Comm</i>	-0.191	-0.622	-1.269	-2.049	-2.893	-3.764	-4.645	-5.528
	<i>Tonight Show w/o Comm</i>	-0.001	-0.233	-0.627	-1.078	-1.547	-2.024	-2.504	-2.986
	<i>Lecture-Gupta</i>	0.114	0.036	-0.224	-0.620	-1.093	-1.605	-2.138	-2.682
	<i>Lecture-Reisslein</i>	0.133	0.041	-0.300	-0.729	-1.185	-1.654	-2.129	-2.608
Q CIF	<i>Citizen Kane</i>	-0.057	-0.106	-0.158	-0.228	-0.326	-0.457	-0.617	-0.797
R.C.	<i>Die Hard I</i>	-0.024	-0.043	-0.054	-0.059	-0.061	-0.061	-0.060	-0.059
256 kbps	<i>Jurassic Park I</i>	-0.047	-0.093	-0.141	-0.195	-0.254	-0.322	-0.396	-0.477
	<i>Silence of the Lambs</i>	-0.096	-0.186	-0.349	-0.664	-1.107	-1.602	-2.110	-2.620
	<i>Star Wars IV</i>	-0.080	-0.150	-0.221	-0.289	-0.356	-0.422	-0.485	-0.548
	<i>Star Wars V</i>	-0.073	-0.146	-0.220	-0.297	-0.375	-0.457	-0.541	-0.629
	<i>The Firm</i>	-0.061	-0.119	-0.175	-0.230	-0.285	-0.342	-0.400	-0.462
	<i>Terminator I</i>	-0.051	-0.094	-0.141	-0.202	-0.281	-0.373	-0.470	-0.569
	<i>Total Recall</i>	-0.062	-0.117	-0.170	-0.222	-0.276	-0.334	-0.396	-0.460
	<i>Aladdin</i>	-0.153	-0.319	-0.502	-0.708	-0.937	-1.185	-1.445	-1.714
	<i>Cinderella</i>	0.019	0.001	-0.180	-0.518	-0.942	-1.402	-1.876	-2.355
	<i>Baseball with Comm</i>	-0.078	-0.162	-0.247	-0.334	-0.425	-0.523	-0.629	-0.744
	<i>Snowboard with Comm</i>	-0.063	-0.147	-0.272	-0.448	-0.674	-0.932	-1.209	-1.498
	<i>Oprah w/o Comm</i>	-0.071	-0.105	-0.124	-0.142	-0.164	-0.192	-0.227	-0.269
	<i>Tonight Show w/o Comm</i>	-0.131	-0.243	-0.344	-0.445	-0.554	-0.677	-0.816	-0.970
	<i>Lecture-Gupta</i>	0.011	0.017	0.014	-0.008	-0.052	-0.113	-0.188	-0.272
	<i>Lecture-Reisslein</i>	0.054	0.092	0.119	0.132	0.127	0.103	0.058	-0.004
CIF	<i>Silence of the Lambs</i>	1.044	1.924	2.724	3.481	4.212	4.925	5.628	6.324
H.Q. No R.C.									
CIF	<i>Silence of the Lambs</i>	0.898	1.721	2.508	3.272	4.021	4.761	5.493	6.219
M.Q. No R.C.									
CIF	<i>Silence of the Lambs</i>	0.483	0.976	1.476	1.988	2.509	3.033	3.555	4.071
L.Q. No R.C.									
CIF	<i>Silence of the Lambs</i>	0.488	0.975	1.469	1.973	2.487	3.005	3.522	4.035
R.C. 64 kbps									
CIF	<i>Silence of the Lambs</i>	0.488	0.975	1.469	1.974	2.488	3.006	3.523	4.035
R.C. 128 kbps									
CIF	<i>Silence of the Lambs</i>	0.515	1.069	1.559	1.963	2.307	2.618	2.910	3.193
R.C. 256 kbps									

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  $Q_n^Y$ ,  $n = 0, \dots, N - 1$ , 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

Enc. M.	Video	Frame Level				GoP level		
		$\bar{Q}$ dB	$CoQV$	$CoQV'$	$Q_{\min}^{\max}$ dB	$CoQV^{(G)}$	$CoQV'^{(G)}$	$Q_{\min}^{\max(G)}$
QCIF	<i>Citizen Kane</i>	37.638	0.491	0.030	31.760	0.267	0.026	17.079
H.Q.	<i>Die Hard I</i>	36.495	13.646	0.021	49.411	3.934	0.015	36.086
No R.C.	<i>Jurassic Park I</i>	36.561	0.197	0.026	14.436	0.158	0.020	6.003
	<i>Silence of the Lambs</i>	37.104	0.186	0.023	18.686	0.160	0.020	12.591
	<i>Star Wars IV</i>	37.073	0.221	0.034	22.776	0.194	0.030	12.008
	<i>Star Wars V</i>	35.986	17.011	0.051	50.579	4.949	0.048	38.759
	<i>The Firm</i>	36.717	0.162	0.020	17.326	0.121	0.014	7.939
	<i>Terminator I</i>	37.045	0.670	0.030	33.085	0.295	0.024	23.851
	<i>Total Recall</i>	36.643	0.182	0.020	27.913	0.116	0.014	13.321
	<i>Aladdin</i>	36.026	0.163	0.024	13.532	0.109	0.016	8.071
	<i>Cinderella</i>	36.154	12.563	0.021	40.847	3.634	0.014	29.675
	<i>Baseball with Comm</i>	35.990	0.204	0.025	42.467	0.123	0.018	12.091
	<i>Snowboard with Comm</i>	36.302	0.521	0.029	34.272	0.239	0.021	21.041
	<i>Oprah w/o Comm</i>	35.688	0.164	0.023	13.260	0.111	0.015	4.424
	<i>Tonight Show w/o Comm</i>	37.674	0.594	0.130	22.366	0.574	0.129	12.518
	<i>Lecture-Gupta</i>	36.215	0.164	0.023	8.609	0.105	0.014	5.865
	<i>Lecture-Reisslein</i>	35.994	0.700	0.046	33.754	0.354	0.042	25.634
QCIF	<i>Jurassic Park I</i>	30.782	0.353	0.054	18.984	0.336	0.052	12.470
M.-L.Q.	<i>Star Wars IV</i>	32.453	0.907	0.050	35.839	0.401	0.048	22.482
No R.C.	<i>The Firm</i>	31.752	0.362	0.047	16.458	0.346	0.045	10.802
	<i>Tonight Show w/o Comm</i>	31.831	0.616	0.165	19.217	0.608	0.165	15.940
QCIF	<i>Citizen Kane</i>	31.050	0.651	0.067	34.129	0.462	0.062	21.777
M.Q.	<i>Die Hard I</i>	30.786	3.685	0.051	43.268	1.104	0.043	29.799
No R.C.	<i>Jurassic Park I</i>	29.458	0.465	0.069	22.130	0.419	0.063	15.633
	<i>Silence of the Lambs</i>	31.888	0.577	0.064	24.458	0.543	0.061	16.900
	<i>Star Wars IV</i>	31.378	1.251	0.060	38.338	0.518	0.054	23.540
	<i>Star Wars V</i>	29.980	0.495	0.084	29.725	0.436	0.079	18.598
	<i>The Firm</i>	30.659	0.490	0.061	17.297	0.450	0.057	12.730
	<i>Terminator I</i>	30.201	0.973	0.068	38.452	0.471	0.059	25.788
	<i>Total Recall</i>	30.628	0.523	0.055	30.171	0.360	0.047	16.189
	<i>Aladdin</i>	28.887	0.542	0.058	31.839	0.335	0.048	15.913
	<i>Cinderella</i>	29.825	2.939	0.053	40.574	0.902	0.044	28.950
	<i>Baseball with Comm</i>	29.650	0.472	0.060	53.192	0.340	0.053	18.248
	<i>Snowboard with Comm</i>	28.986	0.483	0.074	28.438	0.412	0.065	15.010
	<i>Oprah w/o Comm</i>	28.471	0.326	0.053	23.833	0.282	0.045	12.626
	<i>Tonight Show w/o Comm</i>	30.678	0.688	0.185	21.046	0.654	0.184	18.843
	<i>Lecture-Gupta</i>	28.360	0.321	0.055	18.180	0.257	0.041	14.984
	<i>Lecture-Reisslein</i>	27.990	0.505	0.133	29.405	0.453	0.129	21.894
QCIF	<i>Jurassic Park I</i>	26.535	0.438	0.076	22.388	0.427	0.074	17.069
H.-M.Q.	<i>Star Wars IV</i>	28.745	1.097	0.071	36.704	0.537	0.069	23.464
No R.C.	<i>The Firm</i>	27.745	1.099	0.076	18.258	1.102	0.075	14.349
	<i>Tonight Show w/o Comm</i>	27.131	0.662	0.231	23.248	0.657	0.231	21.299
QCIF	<i>Citizen Kane</i>	26.910	0.532	0.082	33.394	0.472	0.081	22.828
L.Q.	<i>Die Hard I</i>	27.132	1.618	0.062	38.709	0.577	0.059	26.407
No R.C.	<i>Jurassic Park I</i>	25.681	0.447	0.080	22.461	0.439	0.078	17.653

Table 6: *continued*

Enc. M.	Video	Frame Level				GoP level		
		$\bar{Q}$ dB	$CoQV$	$CoQV'$	$Q_{\min}^{\max}$ dB	$CoQV^{(G)}$	$CoQV'^{(G)}$	$Q_{\min}^{\max(G)}$
	<i>Silence of the Lambs</i>	28.446	0.679	0.083	21.224	0.666	0.082	18.621
	<i>Star Wars IV</i>	27.892	1.006	0.075	34.876	0.546	0.073	23.119
	<i>Star Wars V</i>	26.604	0.549	0.103	25.701	0.532	0.101	17.965
	<i>The Firm</i>	26.901	0.559	0.083	22.208	0.548	0.081	15.371
	<i>Terminator I</i>	26.457	0.746	0.084	36.370	0.493	0.080	26.615
	<i>Total Recall</i>	27.029	0.434	0.066	25.233	0.388	0.064	15.572
	<i>Aladdin</i>	25.335	0.471	0.077	27.398	0.412	0.074	14.735
	<i>Cinderella</i>	26.094	1.303	0.065	39.998	0.519	0.063	28.318
	<i>Baseball with Comm</i>	26.303	0.444	0.078	37.139	0.398	0.074	18.972
	<i>Snowboard with Comm</i>	25.177	0.499	0.093	29.342	0.479	0.090	16.379
	<i>Oprah w/o Comm</i>	25.248	0.305	0.053	26.889	0.295	0.051	16.180
	<i>Tonight Show w/o Comm</i>	26.214	0.680	0.256	24.988	0.675	0.256	23.386
	<i>Lecture-Gupta</i>	23.846	0.314	0.065	22.052	0.307	0.064	20.034
	<i>Lecture-Reisslein</i>	24.057	0.523	0.160	28.123	0.517	0.159	21.948
QCIF	<i>Citizen Kane</i>	27.383	0.685	0.111	41.183	1.038	0.086	21.405
R.C.	<i>Die Hard I</i>	27.025	1.585	0.064	39.369	1.498	0.060	37.237
64 kbps	<i>Jurassic Park I</i>	25.585	0.451	0.085	25.516	0.915	0.092	21.269
	<i>Silence of the Lambs</i>	28.926	0.830	0.108	29.721	1.297	0.074	31.059
	<i>Star Wars IV</i>	27.935	1.053	0.081	48.171	0.868	0.073	28.030
	<i>Star Wars V</i>	26.512	0.557	0.105	43.121	0.773	0.108	32.013
	<i>The Firm</i>	27.041	0.627	0.099	22.591	0.905	0.077	18.442
	<i>Terminator I</i>	26.355	0.770	0.085	44.135	0.813	0.092	28.454
	<i>Total Recall</i>	26.957	0.446	0.071	36.817	0.656	0.067	17.391
	<i>Aladdin</i>	25.221	0.478	0.078	39.523	0.718	0.084	18.341
	<i>Cinderella</i>	25.981	1.270	0.066	39.695	1.204	0.076	30.015
	<i>Baseball with Comm</i>	26.221	0.448	0.080	37.664	0.594	0.071	20.933
	<i>Snowboard with Comm</i>	25.052	0.498	0.094	26.402	0.745	0.104	23.764
	<i>Oprah w/o Comm</i>	25.145	0.307	0.054	32.042	0.548	0.073	17.812
	<i>Tonight Show w/o Comm</i>	26.539	0.741	0.309	31.522	1.000	0.239	29.026
	<i>Lecture-Gupta</i>	23.693	0.315	0.066	22.177	0.543	0.062	20.274
	<i>Lecture-Reisslein</i>	23.912	0.522	0.158	27.713	0.650	0.155	29.749
QCIF	<i>Citizen Kane</i>	30.773	1.272	0.108	44.167	1.096	0.106	24.928
R.C.	<i>Die Hard I</i>	29.823	3.021	0.087	54.425	1.071	0.083	33.983
128 kbps	<i>Jurassic Park I</i>	28.117	0.792	0.109	24.161	0.777	0.106	21.239
	<i>Silence of the Lambs</i>	31.795	1.330	0.097	33.185	1.311	0.095	29.205
	<i>Star Wars IV</i>	30.978	1.769	0.094	48.617	1.014	0.090	30.358
	<i>Star Wars V</i>	28.801	0.864	0.130	38.917	0.830	0.127	30.477
	<i>The Firm</i>	29.928	0.980	0.101	21.811	0.959	0.099	18.229
	<i>Terminator I</i>	28.380	0.931	0.119	44.868	0.764	0.114	27.924
	<i>Total Recall</i>	29.668	0.766	0.092	36.258	0.686	0.088	17.338
	<i>Aladdin</i>	26.120	0.641	0.105	38.624	0.575	0.101	16.320
	<i>Cinderella</i>	28.075	2.076	0.097	49.343	0.861	0.092	29.716
	<i>Baseball with Comm</i>	28.216	0.664	0.094	53.984	0.591	0.089	20.833
	<i>Snowboard with Comm</i>	26.126	0.668	0.123	41.135	0.640	0.119	20.451
	<i>Oprah w/o Comm</i>	27.082	0.526	0.078	30.006	0.510	0.076	18.064
	<i>Tonight Show w/o Comm</i>	29.173	0.987	0.282	31.345	0.973	0.282	29.179
	<i>Lecture-Gupta</i>	26.450	0.578	0.078	29.221	0.557	0.073	20.866
	<i>Lecture-Reisslein</i>	25.809	0.708	0.183	36.308	0.695	0.182	29.105
QCIF	<i>Citizen Kane</i>	33.458	1.140	0.091	39.732	0.552	0.109	24.207
R.C.	<i>Die Hard I</i>	32.361	5.307	0.068	58.075	0.511	0.060	27.032
256 kbps	<i>Jurassic Park I</i>	30.563	0.939	0.096	23.429	0.378	0.083	20.902
	<i>Silence of the Lambs</i>	33.824	1.398	0.078	36.115	0.791	0.106	18.514
	<i>Star Wars IV</i>	33.338	1.063	0.078	44.470	0.525	0.079	22.974
	<i>Star Wars V</i>	30.995	0.807	0.112	38.956	0.483	0.103	17.925
	<i>The Firm</i>	32.231	0.942	0.082	23.975	0.560	0.097	16.938
	<i>Terminator I</i>	31.157	0.937	0.102	46.188	0.441	0.081	25.758
	<i>Total Recall</i>	32.147	0.722	0.074	40.134	0.339	0.068	15.644
	<i>Aladdin</i>	28.461	0.827	0.093	41.964	0.371	0.075	15.004
	<i>Cinderella</i>	30.472	3.487	0.083	41.801	0.462	0.064	28.030
	<i>Baseball with Comm</i>	30.395	0.639	0.078	51.875	0.350	0.077	19.171

Table 6: *continued*

Enc. M.	Video	Frame Level				GoP level		
		$\bar{Q}$ dB	$CoQV$	$CoQV'$	$Q_{\min}^{\max}$ dB	$CoQV^{(G)}$	$CoQV'^{(G)}$	$Q_{\min}^{\max(G)}$
	<i>Snowboard with Comm</i>	28.692	0.788	0.111	38.684	0.432	0.090	15.592
	<i>Oprah w/o Comm</i>	28.850	0.536	0.077	29.715	0.247	0.052	16.399
	<i>Tonight Show w/o Comm</i>	31.703	1.045	0.239	30.929	0.689	0.309	28.903
	<i>Lecture-Gupta</i>	28.479	0.536	0.072	26.107	0.244	0.065	20.087
	<i>Lecture-Reisslein</i>	27.794	0.655	0.157	37.269	0.464	0.158	20.260
CIF H.Q. No R.C.	<i>Silence of the Lambs</i>	37.896	0.179	0.023	15.978	0.157	0.02	13.809
CIF M.Q. No R.C.	<i>Silence of the Lambs</i>	33.423	0.630	0.063	19.029	0.588	0.06	16.354
CIF L.Q. No R.C.	<i>Silence of the Lambs</i>	30.677	0.786	0.083	21.594	0.753	0.081	19.161
CIF R.C. 64 kbps	<i>Silence of the Lambs</i>	31.095	0.924	0.102	28.151	0.756	0.081	19.117
CIF R.C. 128 kbps	<i>Silence of the Lambs</i>	30.595	0.793	0.084	21.553	0.759	0.081	19.117
CIF R.C. 256 kbps	<i>Silence of the Lambs</i>	30.591	0.793	0.084	21.553	0.887	0.099	19.117

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  $(X_n, Q_n)$ ,  $n = 0, \dots, N - 1$ , 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  $(X_n^{(G)}, Q_n^{(G)})$ ,  $n = 0, \dots, N/G - 1$ , 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 consid-



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

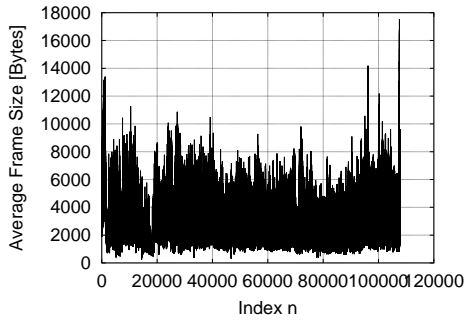
Table 7: *continued*

Enc. M.	Video	Frame Level		GoP level	
		$\rho_{XM}$	$\rho_{XQ}$	$\rho_{XM}^{(G)}$	$\rho_{XQ}^{(G)}$
	<i>Lecture-Reisslein</i>	0.259	-0.264	0.888	-0.829
QCIF	<i>Citizen Kane</i>	0.053	-0.005	0.246	-0.157
R.C.	<i>Die Hard I</i>	0.045	-0.163	0.166	-0.235
64 kbps	<i>Jurassic Park I</i>	0.191	-0.130	0.375	-0.248
	<i>Silence of the Lambs</i>	0.095	-0.018	0.277	-0.131
	<i>Star Wars IV</i>	0.072	-0.079	0.262	-0.248
	<i>Star Wars V</i>	0.193	-0.145	0.411	-0.367
	<i>The Firm</i>	0.081	-0.034	0.244	-0.168
	<i>Terminator I</i>	0.156	-0.191	0.359	-0.356
	<i>Total Recall</i>	0.155	-0.123	0.240	-0.218
	<i>Aladdin</i>	0.276	-0.270	0.599	-0.566
	<i>Cinderella</i>	0.092	-0.251	0.414	-0.490
	<i>Baseball with Comm</i>	0.170	-0.163	0.296	-0.291
	<i>Snowboard with Comm</i>	0.192	-0.196	0.395	-0.403
	<i>Oprah w/o Comm</i>	0.131	-0.089	0.289	-0.223
	<i>Tonight Show w/o Comm</i>	0.076	-0.030	0.299	-0.167
	<i>Lecture-Gupta</i>	0.079	-0.077	0.764	-0.685
	<i>Lecture-Reisslein</i>	0.211	-0.205	0.827	-0.738
QCIF	<i>Citizen Kane</i>	-0.042	0.087	-0.027	0.024
R.C.	<i>Die Hard I</i>	-0.018	0.126	-0.002	0.053
128 kbps	<i>Jurassic Park I</i>	-0.035	0.066	0.141	-0.039
	<i>Silence of the Lambs</i>	-0.021	0.079	0.169	-0.037
	<i>Star Wars IV</i>	-0.033	0.113	-0.005	0.032
	<i>Star Wars V</i>	-0.062	0.084	-0.020	0.024
	<i>The Firm</i>	-0.050	0.088	-0.008	0.018
	<i>Terminator I</i>	-0.028	0.083	0.104	-0.042
	<i>Total Recall</i>	-0.066	0.105	-0.036	0.035
	<i>Aladdin</i>	-0.013	0.074	0.162	-0.089
	<i>Cinderella</i>	-0.018	0.120	0.111	-0.026
	<i>Baseball with Comm</i>	-0.081	0.122	-0.009	0.018
	<i>Snowboard with Comm</i>	-0.040	0.082	0.076	-0.040
	<i>Oprah w/o Comm</i>	-0.079	0.103	-0.012	0.024
	<i>Tonight Show w/o Comm</i>	-0.044	0.019	0.025	0.001
	<i>Lecture-Gupta</i>	-0.184	0.292	0.038	-0.014
	<i>Lecture-Reisslein</i>	-0.122	0.082	0.042	-0.030
QCIF	<i>Citizen Kane</i>	-0.112	0.178	-0.047	0.051
R.C.	<i>Die Hard I</i>	-0.027	0.291	-0.009	0.082
256 kbps	<i>Jurassic Park I</i>	-0.117	0.172	-0.030	0.042
	<i>Silence of the Lambs</i>	-0.085	0.193	-0.026	0.049
	<i>Star Wars IV</i>	-0.122	0.222	-0.031	0.060
	<i>Star Wars V</i>	-0.171	0.176	-0.071	0.054
	<i>The Firm</i>	-0.131	0.204	-0.041	0.049
	<i>Terminator I</i>	-0.171	0.229	-0.045	0.064
	<i>Total Recall</i>	-0.192	0.262	-0.075	0.073
	<i>Aladdin</i>	-0.178	0.265	-0.086	0.076
	<i>Cinderella</i>	-0.037	0.246	0.062	0.023
	<i>Baseball with Comm</i>	-0.219	0.273	-0.084	0.071
	<i>Snowboard with Comm</i>	-0.191	0.221	-0.058	0.055
	<i>Oprah w/o Comm</i>	-0.188	0.214	-0.070	0.064
	<i>Tonight Show w/o Comm</i>	-0.114	0.044	-0.051	0.014
	<i>Lecture-Gupta</i>	-0.331	0.430	-0.074	0.076
	<i>Lecture-Reisslein</i>	-0.267	0.158	-0.033	0.018
CIF H.Q. No R.C.	<i>Silence of the Lambs</i>	0.435	-0.363	0.765	-0.669
CIF M.Q. No R.C.	<i>Silence of the Lambs</i>	0.436	-0.365	0.829	-0.738
CIF L.Q.	<i>Silence of the Lambs</i>	0.528	-0.456	0.650	-0.585

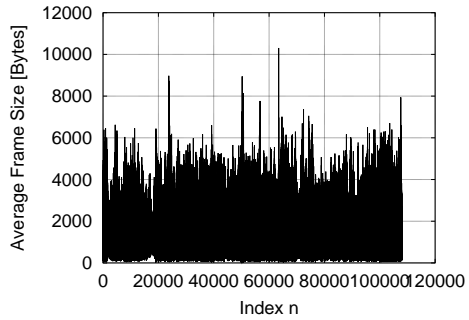
Table 7: *continued*

Enc. M.	Video	Frame Level		GoP level	
		$\rho_{XM}$	$\rho_{XQ}$	$\rho_{XM}^{(G)}$	$\rho_{XQ}^{(G)}$
No R.C.					
CIF R.C. 64 kbps	<i>Silence of the Lambs</i>	0.527	-0.455	0.646	-0.583
CIF R.C. 128 kbps	<i>Silence of the Lambs</i>	0.527	-0.455	0.647	-0.584
CIF R.C. 256 kbps	<i>Silence of the Lambs</i>	0.274	-0.140	0.480	-0.317

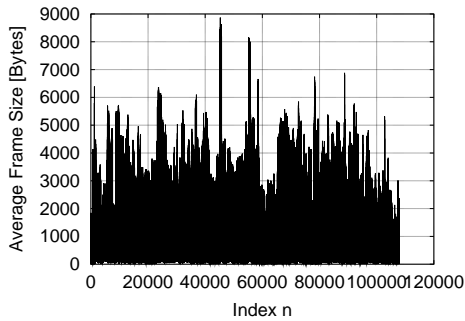
Figure 19 gives rate-distortion plots, i.e., the average video quality  $\bar{Q}$  as a function of the mean bit rate. The plots are obtained from the five different quality level encodings of four different videos.



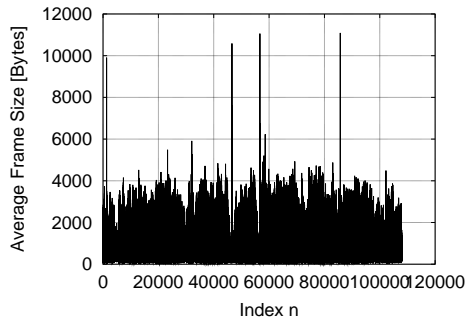
a) *Star Wars IV* with high quality



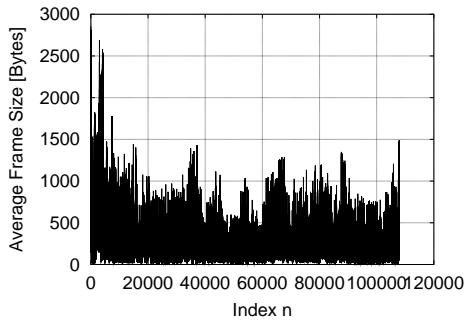
d) *Star Wars IV* with 256 kbps target bit rate



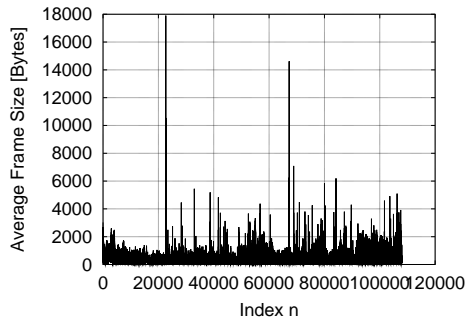
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality

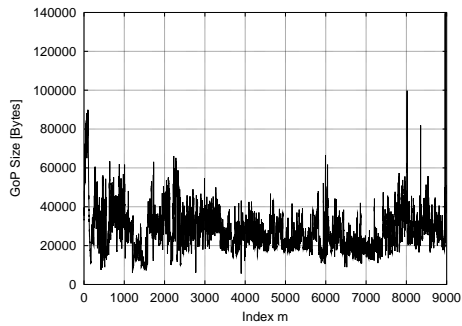


f) *Silence of the Lambs* with 64 kbps target bit rate

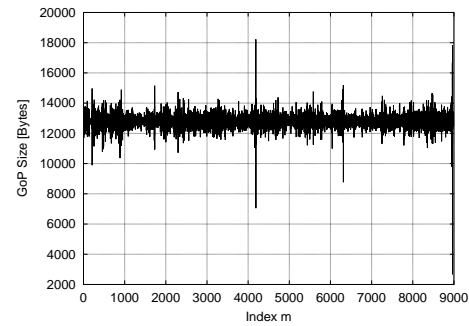
Encoding without rate control

Encoding with rate control

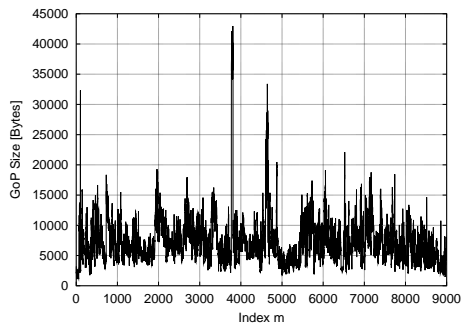
Figure 1: Frame size  $X_n$  as a function of the frame index  $n$  for single-layer QCIF video.



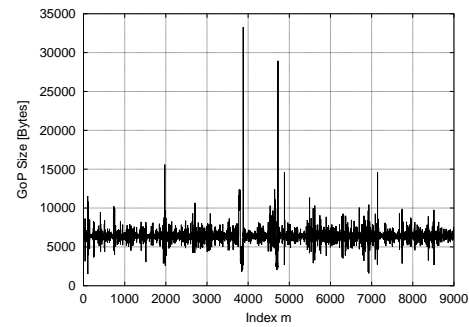
a) *Star Wars IV* with high quality



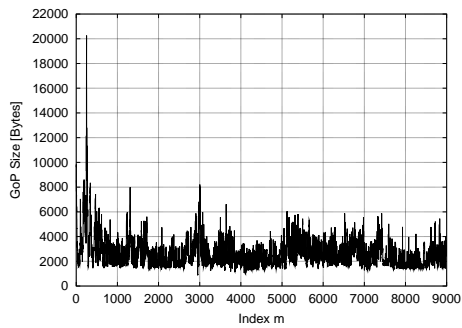
d) *Star Wars IV* with 256 kbps target bit rate



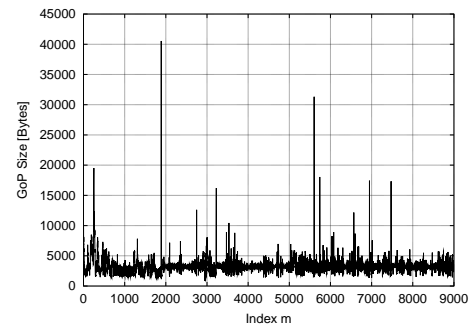
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality

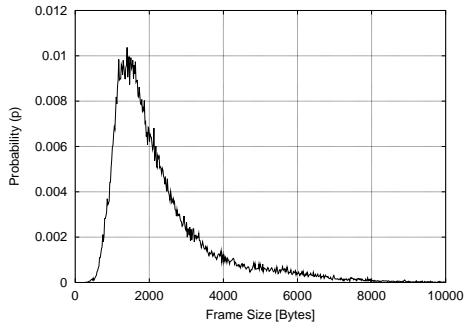


f) *Silence of the Lambs* with 64 kbps target bit rate

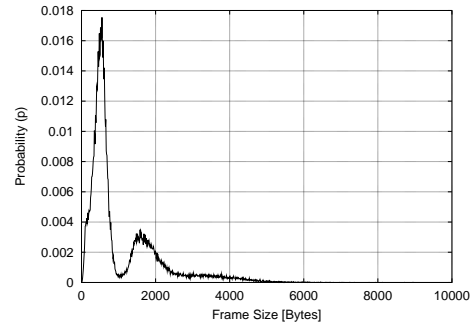
Encoding without rate control

Encoding with rate control

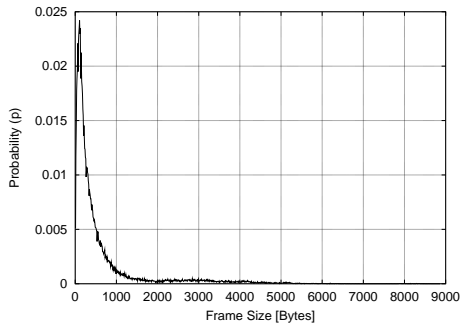
Figure 2: GoP size  $Y_m$  as a function of the index  $m$  for single-layer QCIF video.



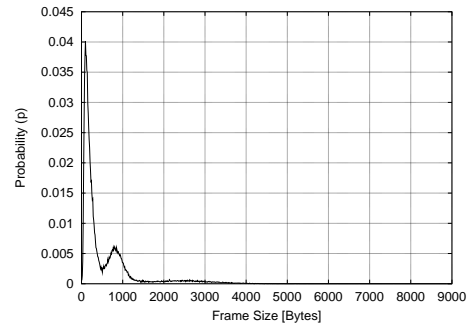
a) *Star Wars IV* with high quality



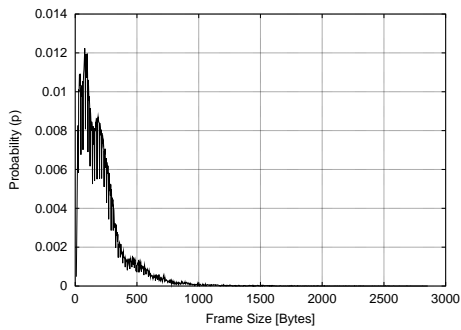
d) *Star Wars IV* with 256 kbps target bit rate



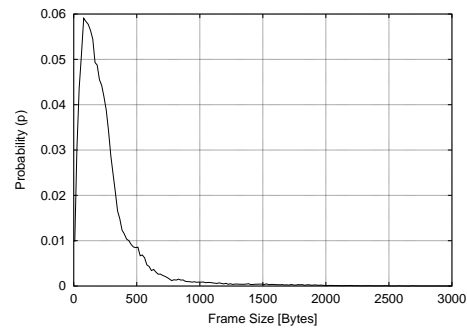
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality



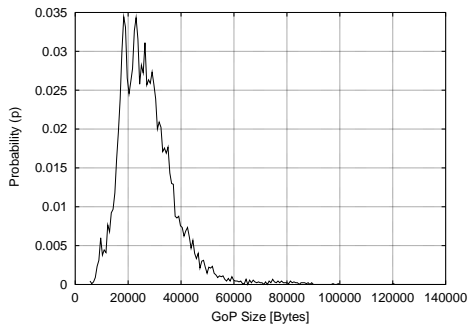
f) *Silence of the Lambs* with 64 kbps target bit rate

Encoding without rate control

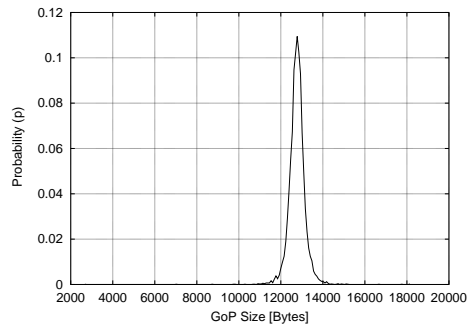
Encoding with rate control

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

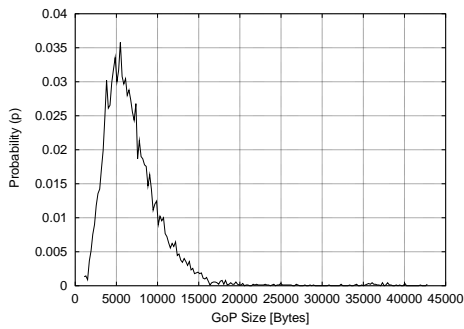




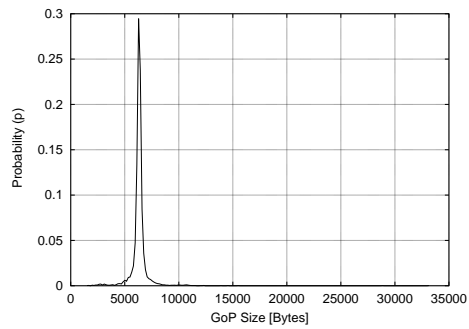
a) *Star Wars IV* with high quality



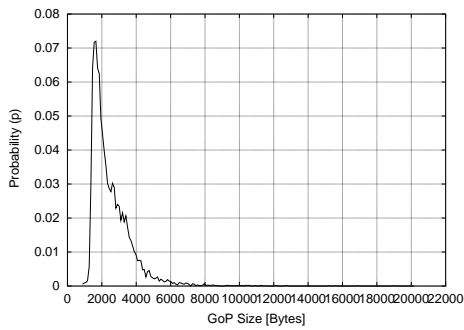
d) *Star Wars IV* with 256 kbps target bit rate



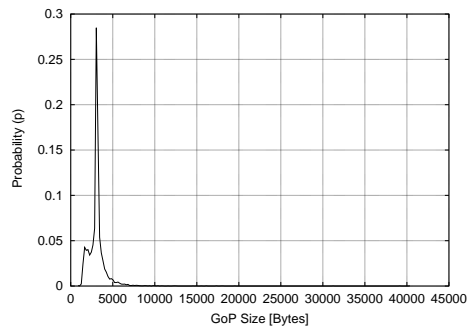
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality

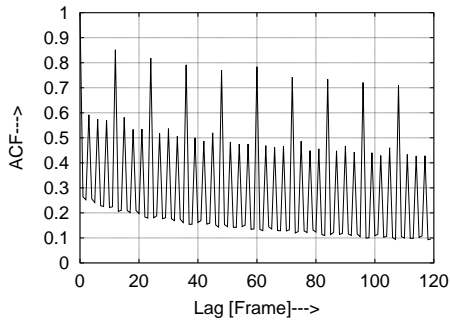


f) *Silence of the Lambs* with 64 kbps target bit rate

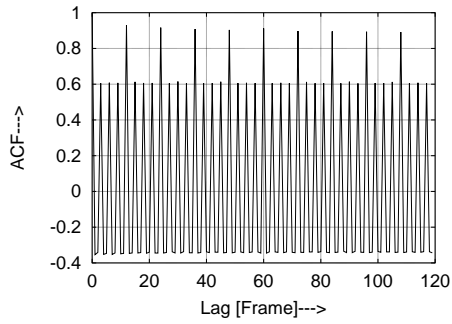
Encoding without rate control

Encoding with rate control

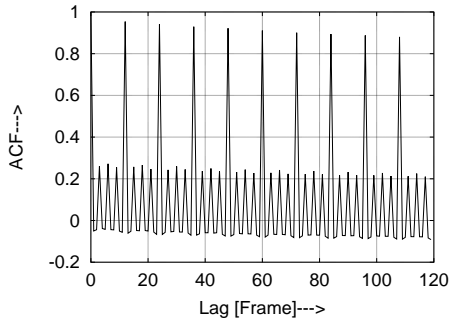
Figure 4: GoP size histograms for single-layer QCIF video.



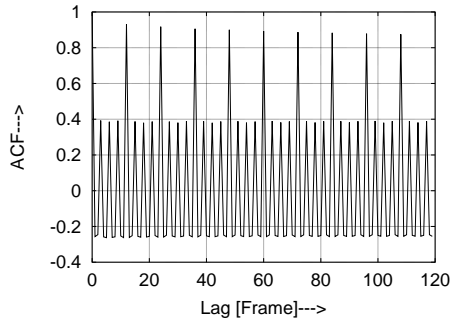
a) *Star Wars IV* with high quality



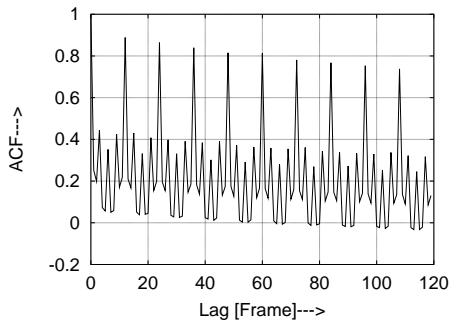
d) *Star Wars IV* with 256 kbps target bit rate



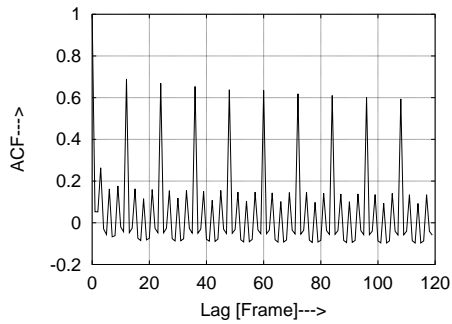
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality

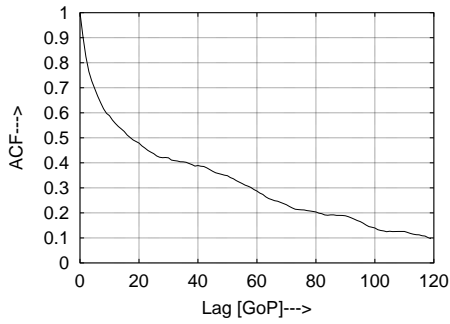


f) *Silence of the Lambs* with 64 kbps target bit rate

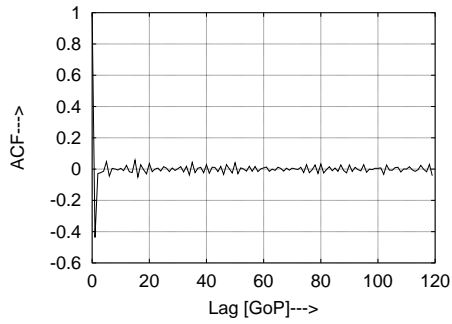
Encoding without rate control

Encoding with rate control

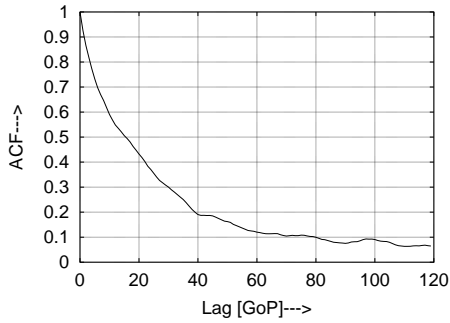
Figure 5: Frame size autocorrelations for single-layer QCIF video.



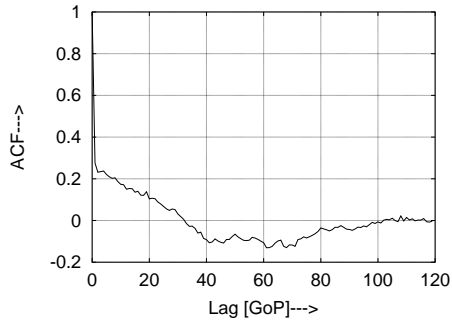
a) *Star Wars IV* with high quality



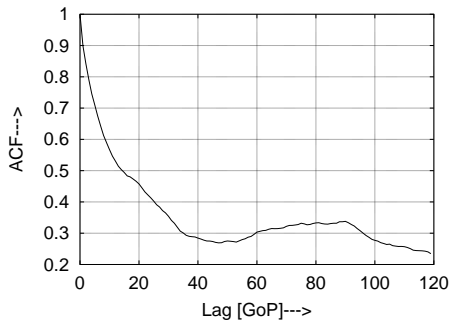
d) *Star Wars IV* with 256 kbps target bit rate



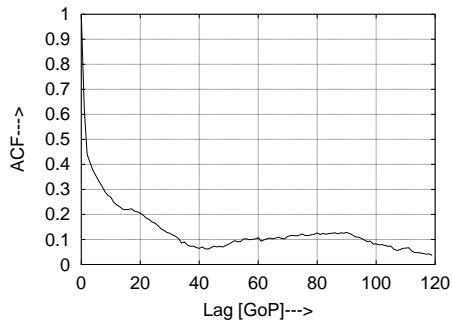
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality

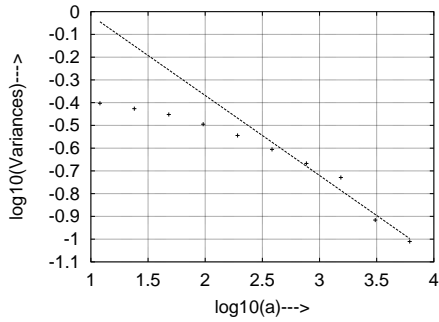


f) *Silence of the Lambs* with 64 kbps target bit rate

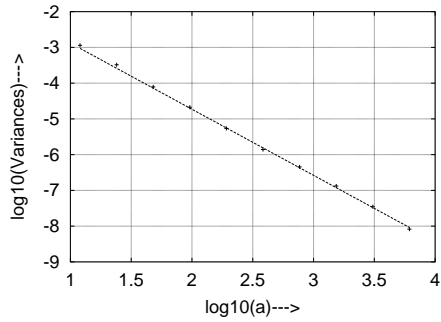
Encoding without rate control

Encoding with rate control

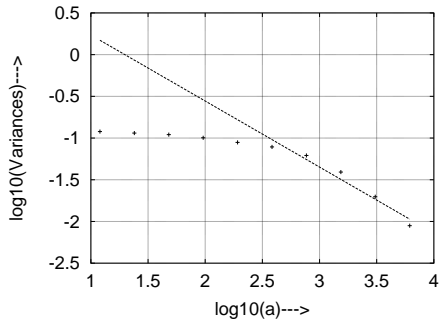
Figure 6: GoP size autocorrelations for single-layer QCIF video.



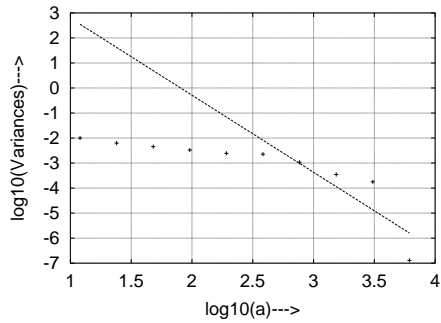
a) *Star Wars IV* with high quality,  $H=0.824$



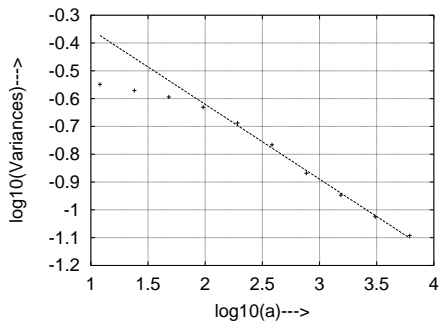
d) *Star Wars IV* with 256 kbps target bit rate,  $H=0.075$



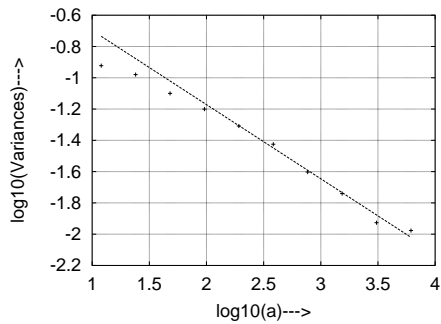
b) *Jurassic Park I* with medium quality,  $H=0.604$



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



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

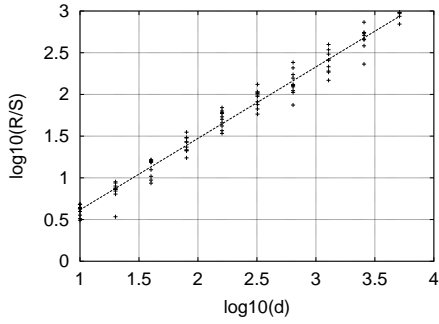


f) *Silence of the Lambs* with 64 kbps target bit rate,  $H=0.763$

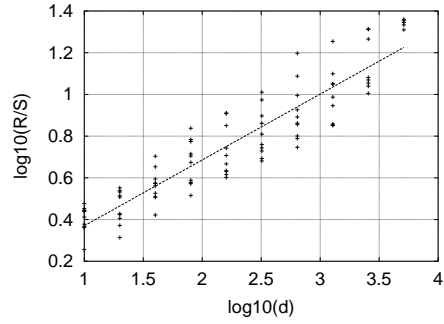
Encoding without rate control

Encoding with rate control

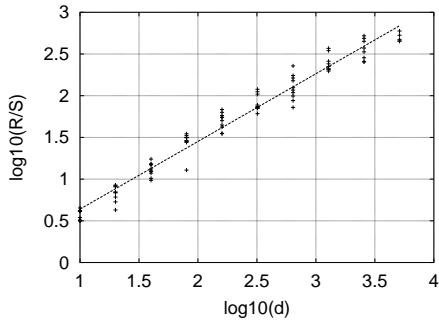
Figure 7: Variance time plots for single-layer QCIF video.



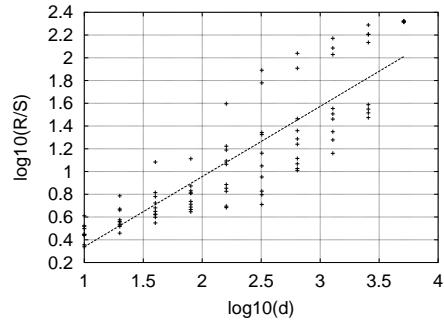
a) *Star Wars IV* with high quality,  $H=0.856$



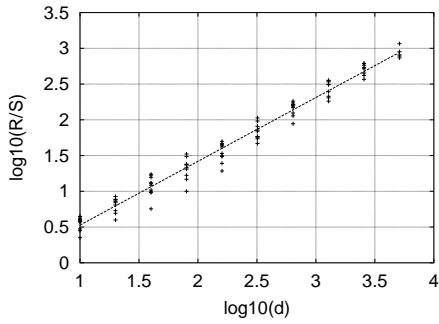
d) *Star Wars IV* with 256 kbps target bit rate,  $H=0.657$



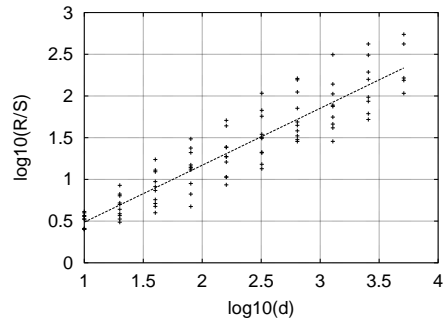
b) *Jurassic Park I* with medium quality,  $H=0.811$



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



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

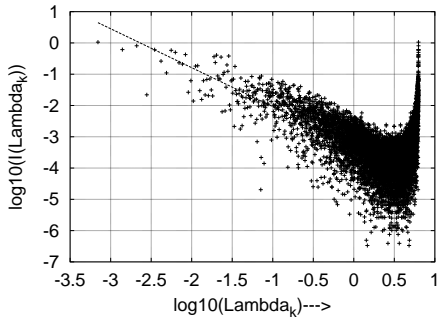


f) *Silence of the Lambs* with 64 kbps target bit rate,  $H=0.316$

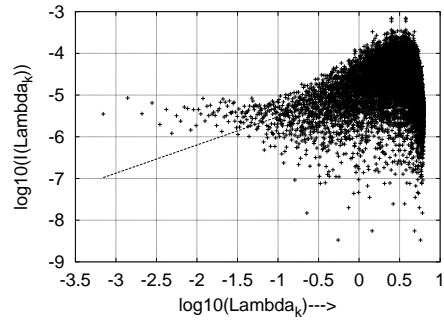
Encoding without rate control

Encoding with rate control

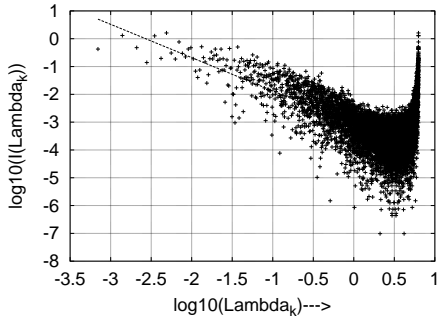
Figure 8: Pox plots of  $R/S$  for aggregation level  $a = 12$  for single-layer QCIF video.



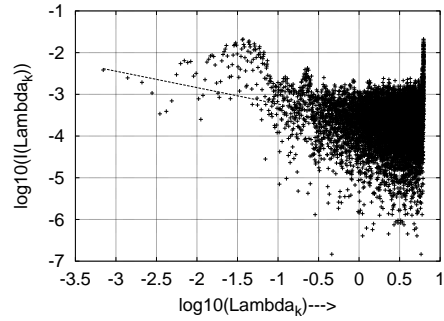
a) *Star Wars IV* with high quality,  $H=1.122$



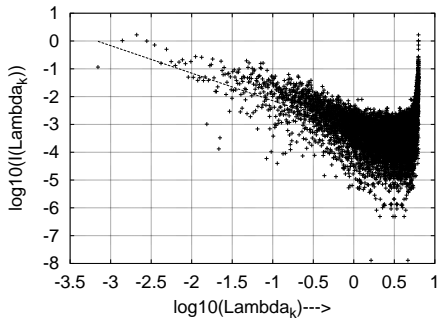
d) *Star Wars IV* with 256 kbps target bit rate,  $H=0.162$



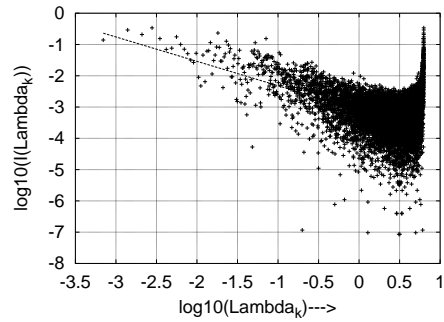
b) *Jurassic Park I* with medium quality,  $H=1.098$



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



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

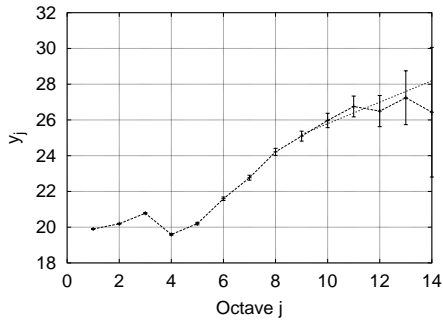


f) *Silence of the Lambs* with 64 kbps target bit rate,  $H=0.889$

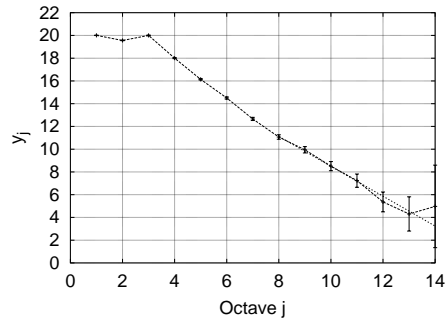
Encoding without rate control

Encoding with rate control

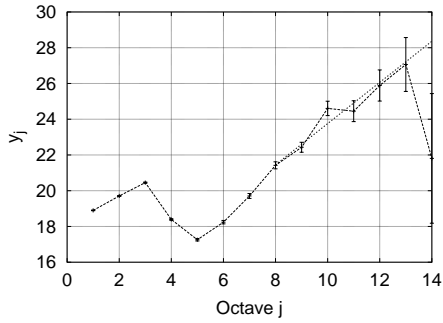
Figure 9: Periodogram for aggregation level  $a = 12$  for single-layer QCIF video.



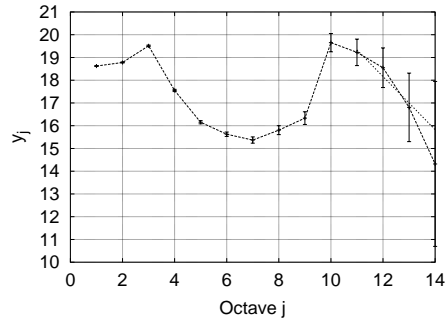
a) *Star Wars IV* with high quality



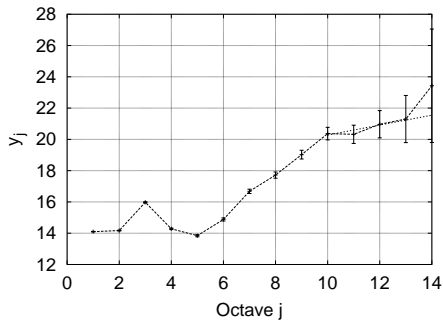
d) *Star Wars IV* with 256 kbps target bit rate



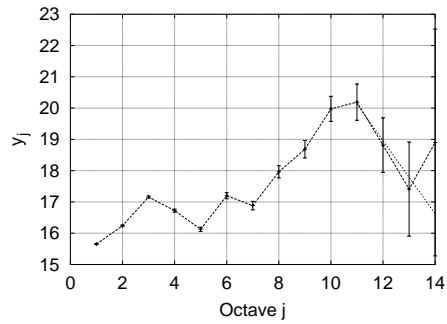
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality

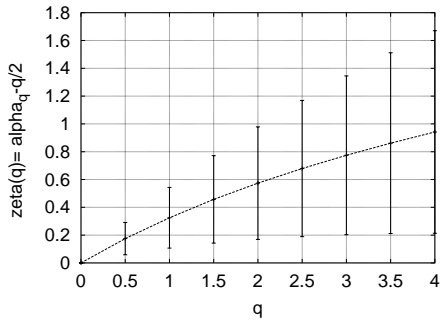


f) *Silence of the Lambs* with 64 kbps target bit rate

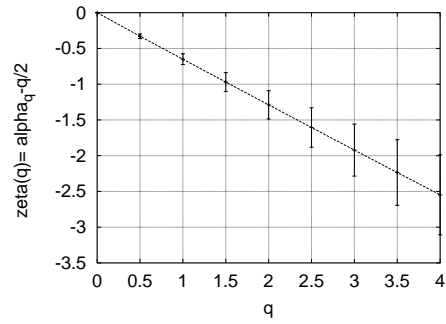
Encoding without rate control

Encoding with rate control

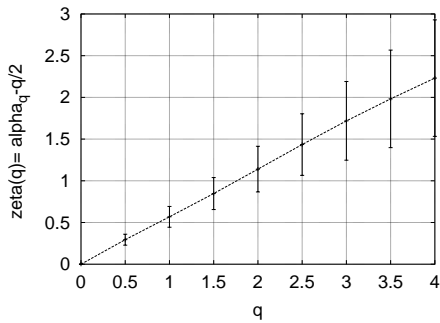
Figure 10: Logscale diagrams for single-layer QCIF video.



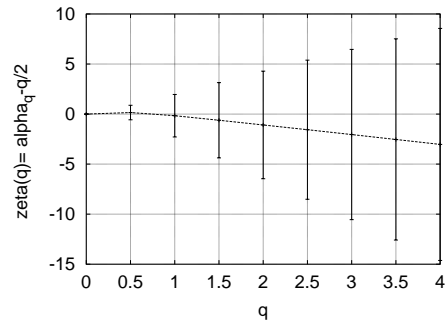
a) *Star Wars IV* with high quality



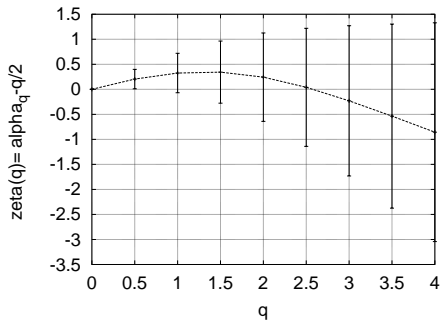
d) *Star Wars IV* with 256 kbps target bit rate



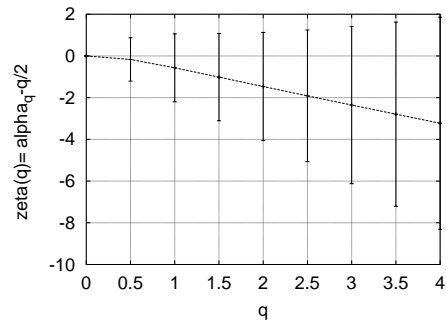
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality



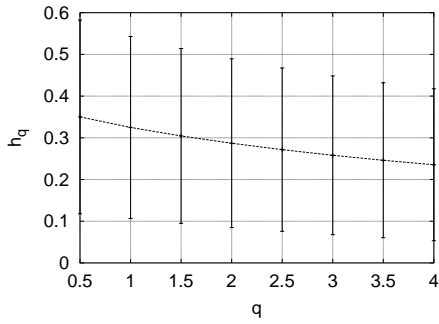
f) *Silence of the Lambs* with 64 kbps target bit rate

Encoding without rate control

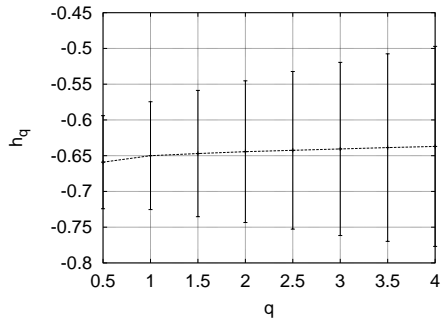
Encoding with rate control

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

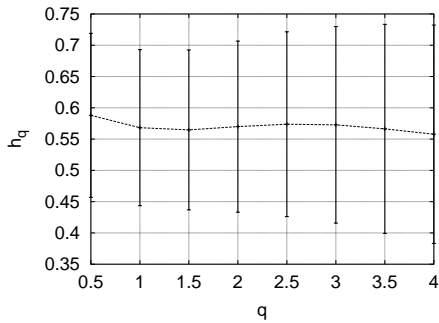




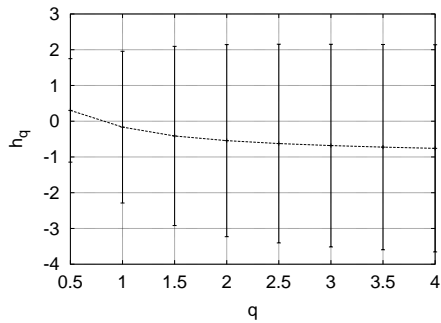
a) *Star Wars IV* with high quality



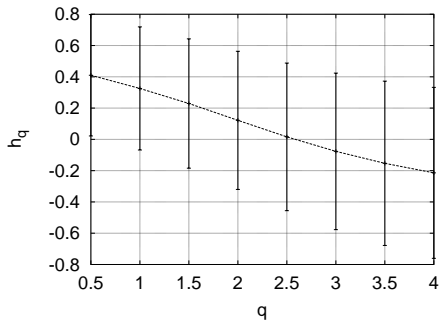
d) *Star Wars IV* with 256 kbps target bit rate



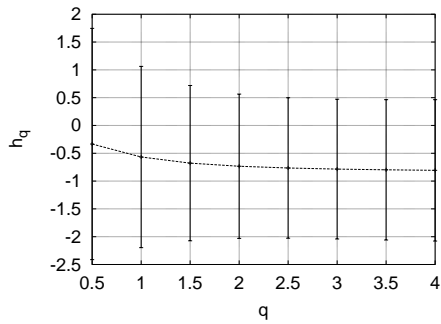
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality

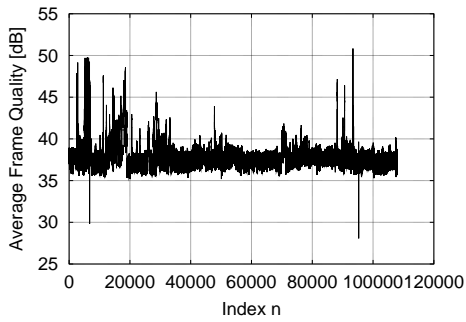


f) *Silence of the Lambs* with 64 kbps target bit rate

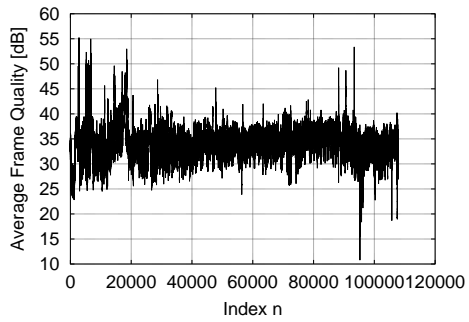
Encoding without rate control

Encoding with rate control

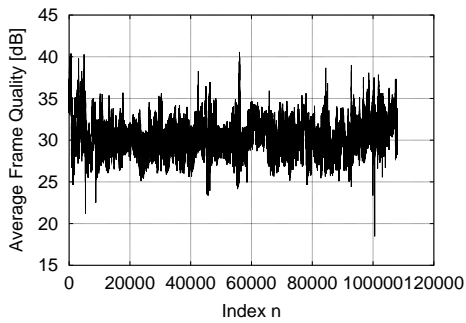
Figure 12: Linear multiscale diagrams for single-layer QCIF video.



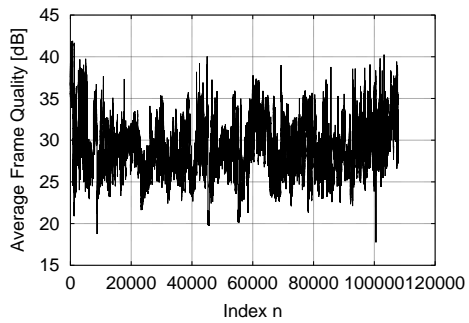
a) *Star Wars IV* with high quality



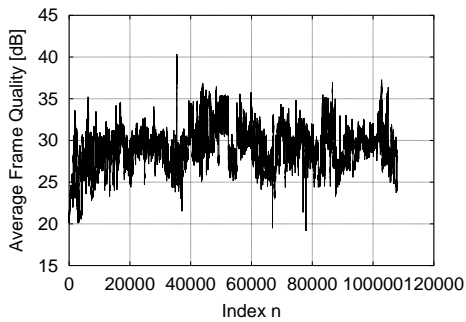
d) *Star Wars IV* with 256 kbps target bit rate



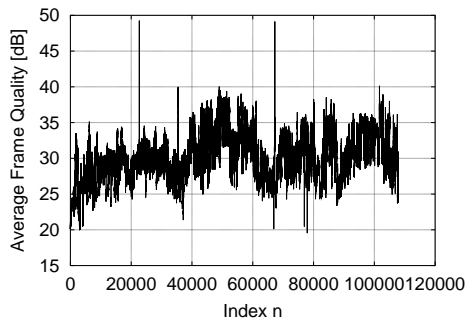
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality

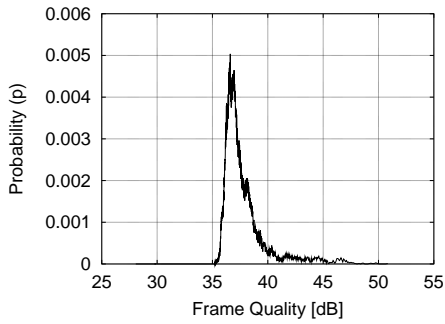


f) *Silence of the Lambs* with 64 kbps target bit rate

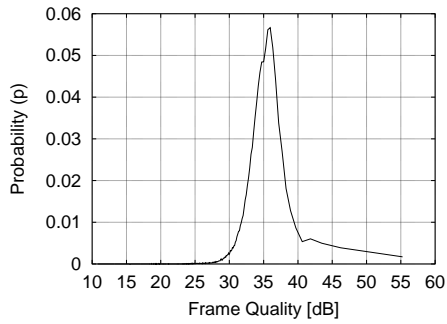
Encoding without rate control

Encoding with rate control

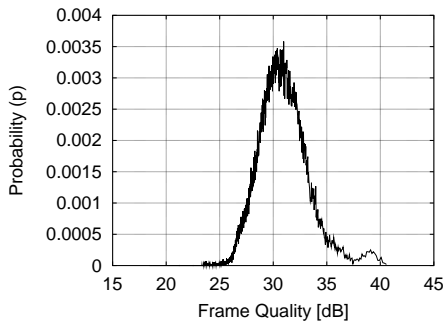
Figure 13: Video frame quality  $Q_n$  (in dB) as a function of the frame index  $n$  for single-layer QCIF video.



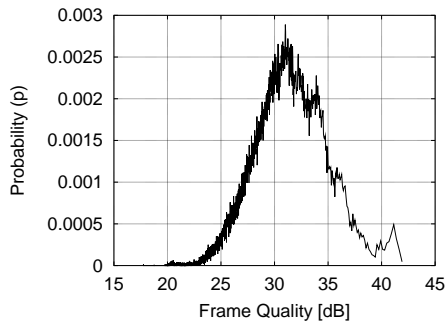
a) *Star Wars IV* with high quality



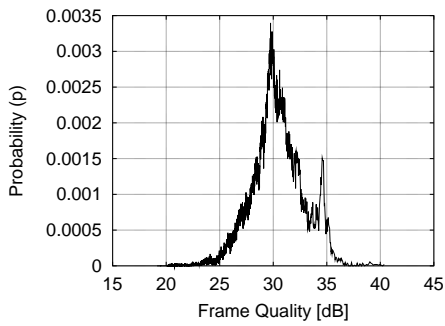
d) *Star Wars IV* with 256 kbps target bit rate



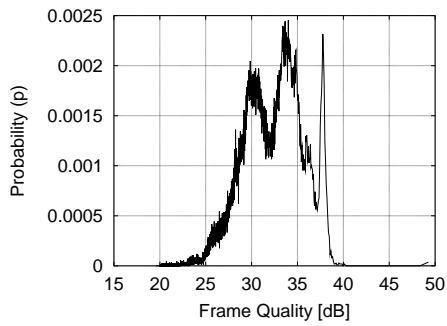
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality

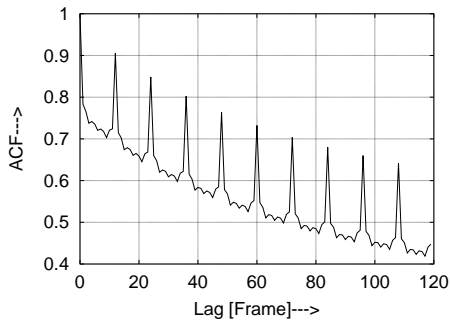


f) *Silence of the Lambs* with 64 kbps target bit rate

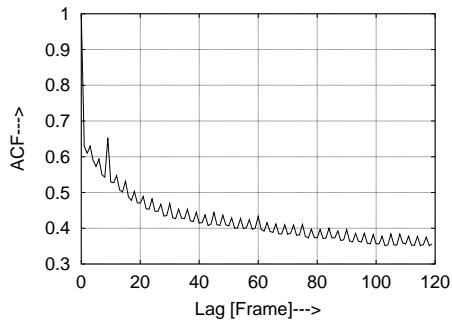
Encoding without rate control

Encoding with rate control

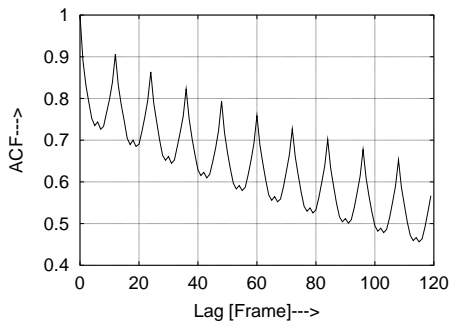
Figure 14: Histograms of video frame quality  $Q_n$  (in dB) of single-layer QCIF video.



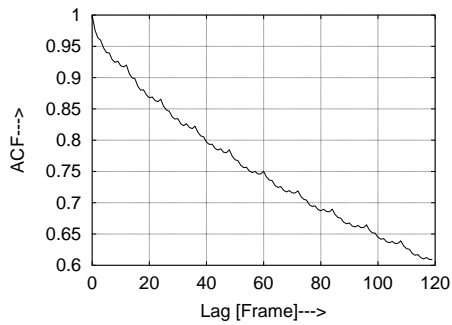
a) *Star Wars IV* with high quality



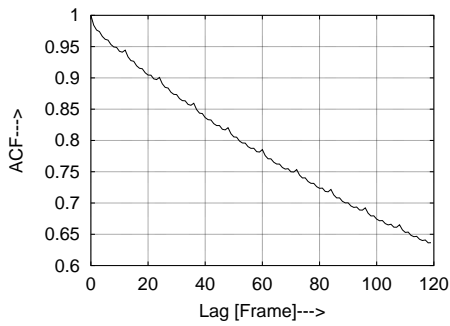
d) *Star Wars IV* with 256 kbps target bit rate



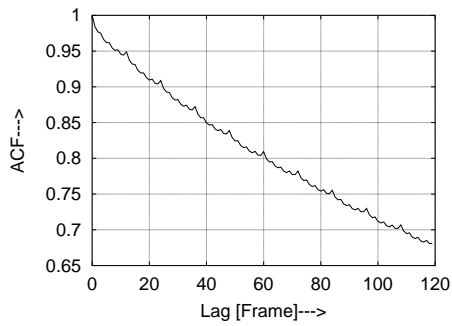
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality

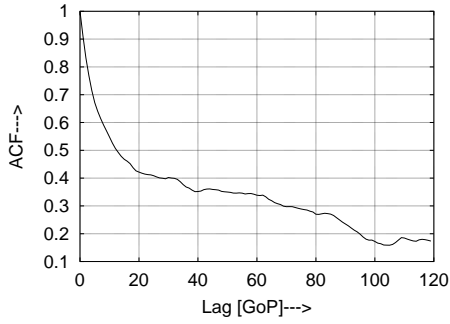


f) *Silence of the Lambs* with 64 kbps target bit rate

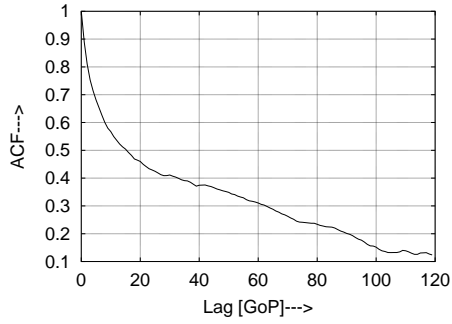
Encoding without rate control

Encoding with rate control

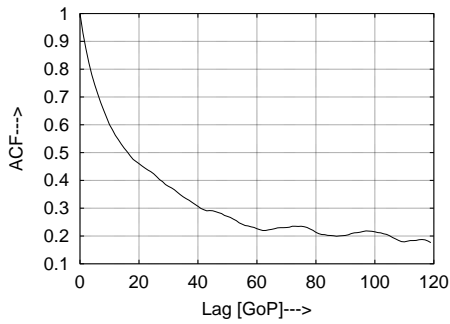
Figure 15: MSE autocorrelation coefficient  $\rho_M(k)$  as as function of the lag  $k$  (in frames) for single-layer QCIF video.



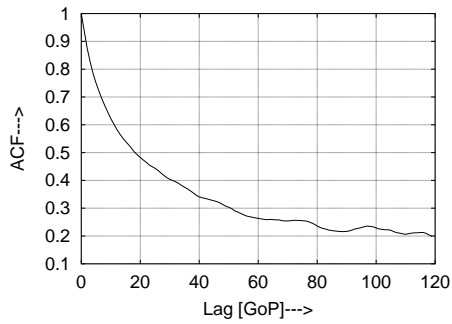
a) *Star Wars IV* with high quality



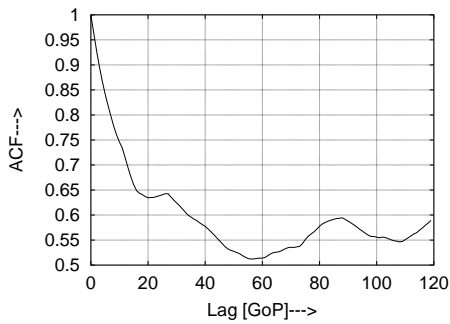
d) *Star Wars IV* with 256 kbps target bit rate



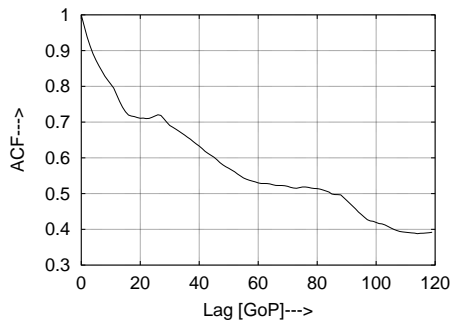
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality

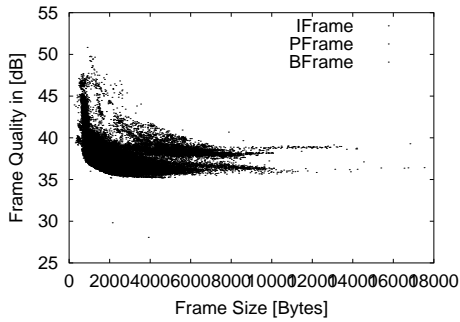


f) *Silence of the Lambs* with 64 kbps target bit rate

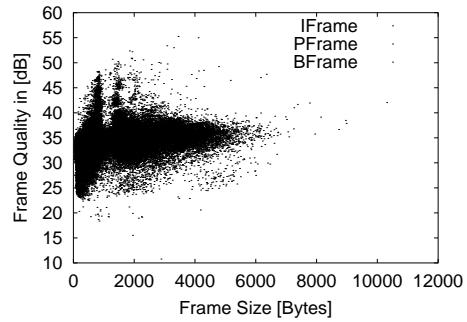
Encoding without rate control

Encoding with rate control

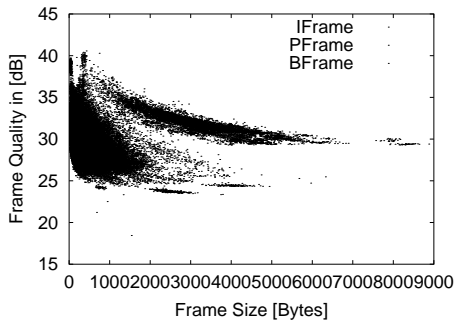
Figure 16: MSE autocorrelation coefficient  $\rho_M^{(G)}(k)$  as a function of the lag  $k$  (in GoPs) for single-layer QCIF video.



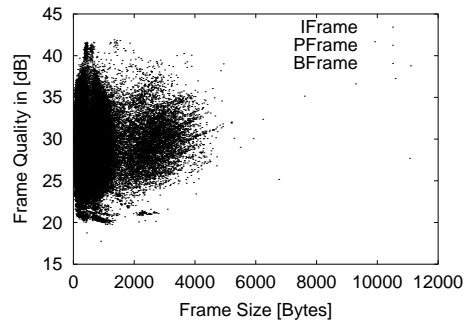
a) *Star Wars IV* with high quality



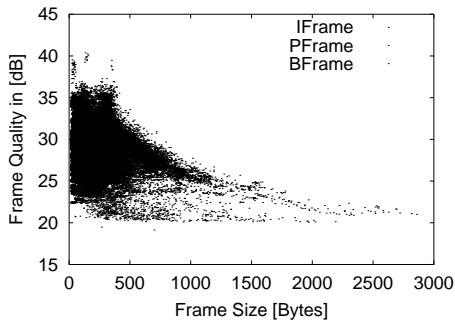
d) *Star Wars IV* with 256 kbps target bit rate



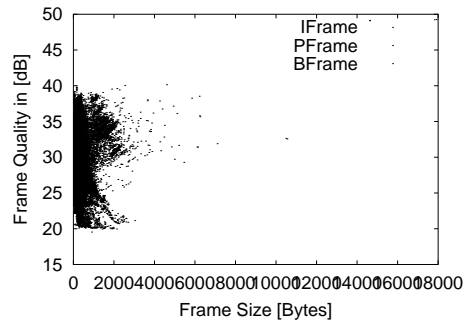
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality

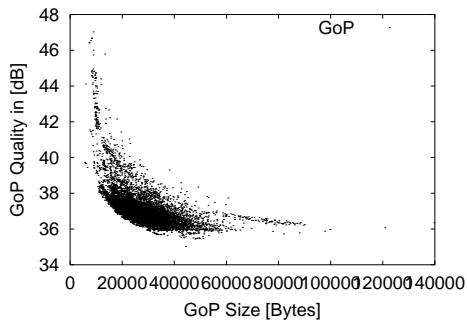


f) *Silence of the Lambs* with 64 kbps target bit rate

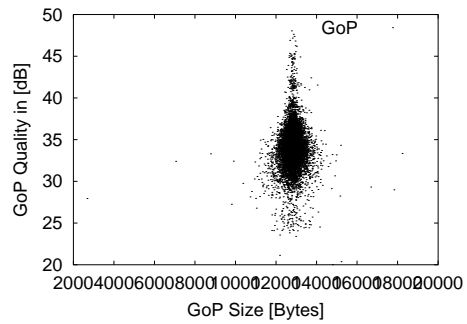
Encoding without rate control

Encoding with rate control

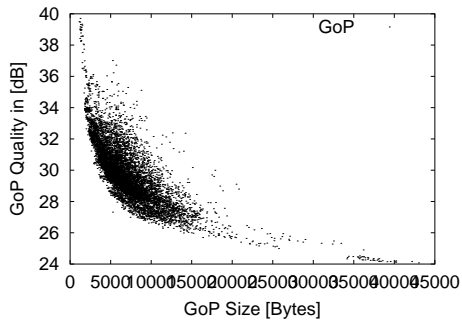
Figure 17: Scatter plots of frame size and frame quality for single-layer QCIF video.



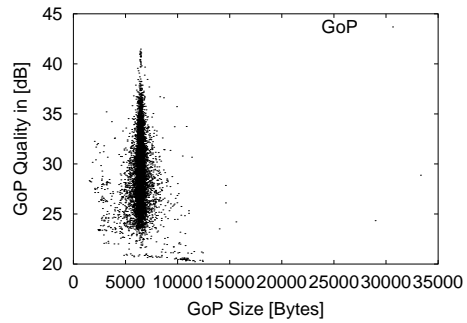
a) *Star Wars IV* with high quality



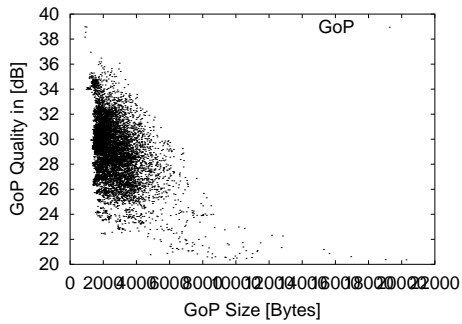
d) *Star Wars IV* with 256 kbps target bit rate



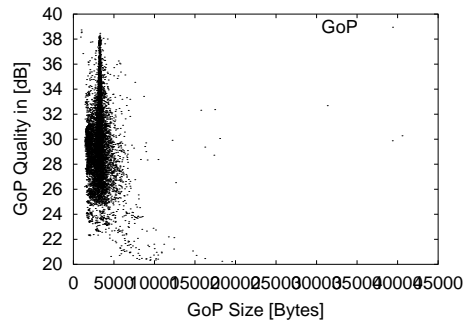
b) *Jurassic Park I* with medium quality



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



c) *Silence of the Lambs* with low quality



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

Encoding without rate control

Encoding with rate control

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

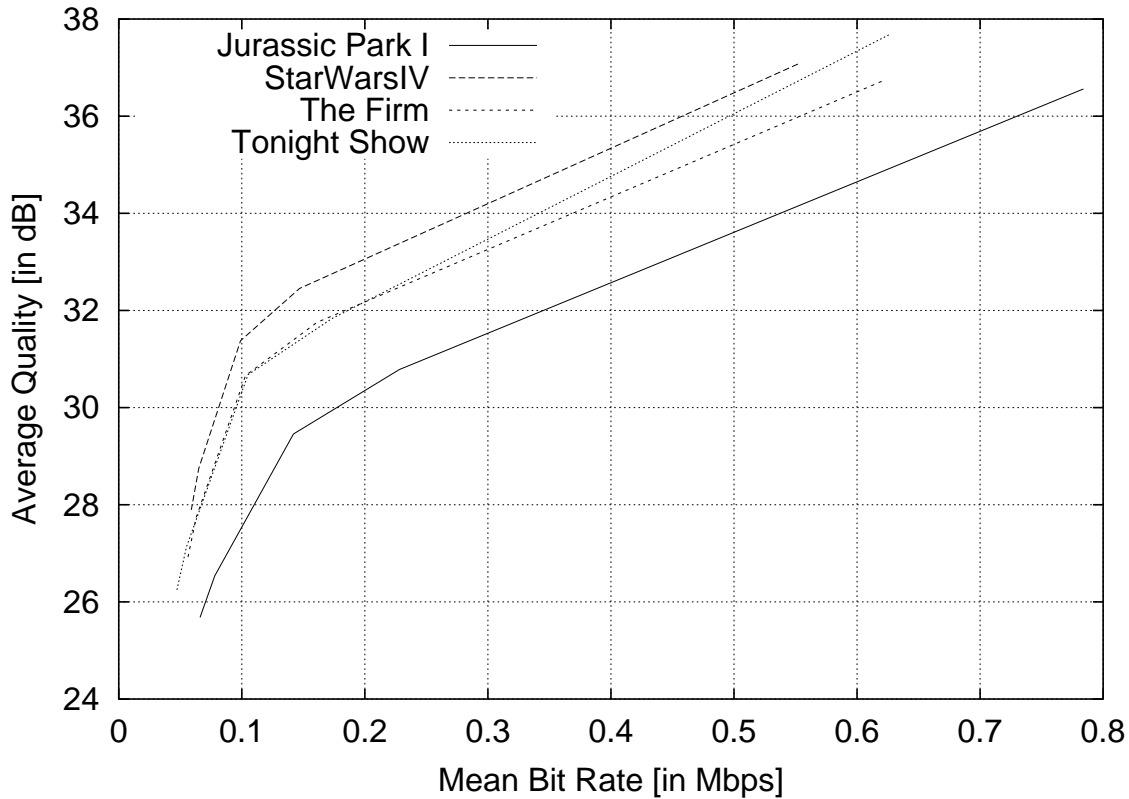


Figure 19: Rate-distortion plot for single-layer QCIF video.

## 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  $k$ ,  $k = 0, 1, \dots, N-1$ , 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 perform 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 long 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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