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Simple and Efficient Models for Variable Bit Rate MPEG Video Traffic

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Abstract

For the performance analysis of ATM networks carrying Variable Bit Rate (VBR) MPEG video sequences there is a need for appropriate video traffic models. In this paper, we discuss Markov chain models for this specific type of traffic with respect to several statistical properties and their ability to predict cell losses at buffers of ATM multiplexers. We intentionally selected a simple model class to check for its appropriateness to model a complex traffic type. The results of this paper show that Markov chain models can be used efficiently for MPEG video traffic under the following conditions. The Group of Pictures (GOP) generation process should be modeled rather than the frame process. If the performance measures depend on the correlation properties of the video traffic the scene process should also be considered in the course of the model development.

1 Introduction

In B-ISDNs on the basis of the ATM, a major part of the traffic will be generated by multimedia sources like teleconferencing terminals and video-on-demand servers. Most of the video encoding will be done using the MPEG standard (ISO Moving Picture Expert Group).

To analyze the performance of these networks either by means of analysis or simulation, there is a need for video traffic models. CBR (Constant Bit Rate) video traffic models are trivial from statistical modeling point of view. Therefore, most papers about video modeling focus on VBR (Variable Bit Rate) video traffic. A wide range of models, from traditional Markov chains to new approaches such as fractal models, can be found in the teletraffic literature.

In this study, we examine three Markov chain models for VBR MPEG video traffic, which are of different complexity. The main difference of the models is their capability to approximate the autocorrelation function of the GOP sizes of a given empirical MPEG data set. We consider the strength and the limitations of this model class with respect to several statistical properties and the ability to predict cell losses at an ATM multiplexer buffer.

The paper is organized as follows. Section 2 provides an outline of MPEG video encoding and its impact on the statistical properties of the video traffic. In Section 3 a short overview on the current video modeling literature is given. The video traffic models, which are considered for this study, the estimation of the model parameters and the statistical properties of these models are presented in Section 4. Section 5 contains a comparison of the cell loss estimation quality of the models, and in Section 6 the applicability of higher-order Markov chains for video modeling is studied. Section 7 concludes the paper.

2 MPEG video traffic properties

Due to the high bandwidth needs of uncompressed video data streams, several coding algorithms for the compression of these streams were developed. At the moment, the

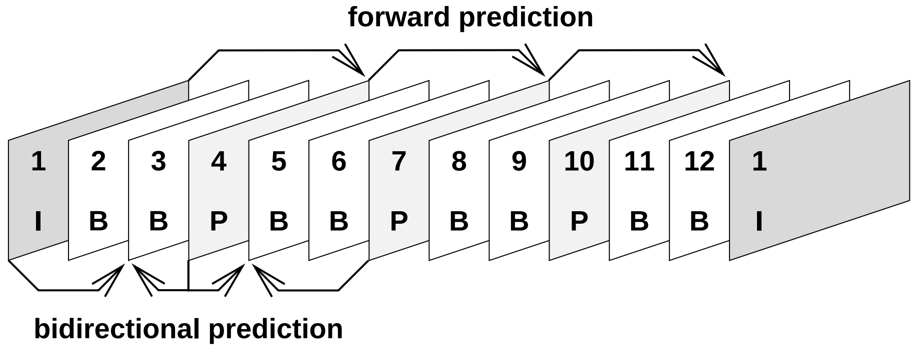

Figure 1: *Group of Pictures of an MPEG stream*

MPEG coding scheme is widely used for any type of video applications. There are two schemes, MPEG-I [8, 7] and MPEG-II [3], where the MPEG-I functionalities are a subset of the MPEG-II ones. The main difference with respect to video transmission on ATM is that MPEG-II allows for layered coding. This means that the video data stream consists of a base layer stream which contains the most important video data, and of one or more enhancement layers which can be used to improve the quality of the video sequence.

In this paper, we focus on one-layer video data streams of MPEG-I type. Most of the encoders will use this scheme and in case of multi-layer encoding the statistical properties of the base layer will be almost identical to this type of stream.

The MPEG compression is done by reducing both the spatial and the temporal redundancy of the video data stream. The spatial redundancies are reduced by transforms and entropy coding and the temporal redundancies are reduced by the prediction of future frames based on motion vectors. This is achieved using three types of frames (cf. Fig. 1):

I-frames use only intra-frame coding, based on the discrete cosine transform and entropy coding;

P-frames use a similar coding algorithm to I-frames, but with the addition of motion compensation with respect to the previous I- or P-frame;

B-frames are similar to P-frames, except that the motion compensation can be with respect to the previous I- or P-frame, the next I- or P-frame, or an interpolation between them.

	Frames				GOPs
	I	P	B	all	
Mean [bits]	60,144	23,192	7,216	15,599	187,185
CoV	0.33	0.64	0.67	1.16	0.39
Peak/Mean	3.1	7.6	8.7	11.9	0.39

Table 1: *Statistical data of the Star Wars MPEG sequence*

Typically, I-frames require more bits than P-frames. B-frames have the lowest bandwidth requirements. Due to the MPEG coding technique, the frames are arranged in a deterministic periodic sequence, e.g. “IBBPBB” or “IBBPBBPBBPBB”, which is called *Group of Pictures* (GOP). The length of a GOP refers to the number of frames of one GOP.

This coding scheme leads to a variety of statistical properties which are typical only for MPEG video traffic streams. A detailed description of these properties can be found in [14].

As empirical MPEG video data sets for this study we used both our own data sets [1] and the *Star Wars* data set from Bellcore [5]. We will only report results for the *Star Wars* data set, because it is widely used and we obtained essentially the same results for all data sets.

Tab. 1 contains some basic statistical data of the frame and the GOP sizes of the *Star Wars* sequence. The average bit rate of this sequence is about 0.36 Mbps. Fig. 2 and Fig. 3 show the autocorrelation functions for the frame sizes and the GOP sizes. The shape of the curve in Fig. 2 is the result of the periodic coding pattern and the different mean frame sizes of the frame types. The most important property of the GOP correlation curve in Fig. 3 is its slow decay behavior for larger lags, which is clearly not exponential and therefore indicates long-range dependences. In the GOP case, a lag of one hundred is approximately equivalent to 40 seconds, and the coefficient of correlation is still high.

[1] These MPEG data sets are available via anonymous ftp:

`ftp://ftp-info3.informatik.uni-wuerzburg.de/pub/MPEG/`

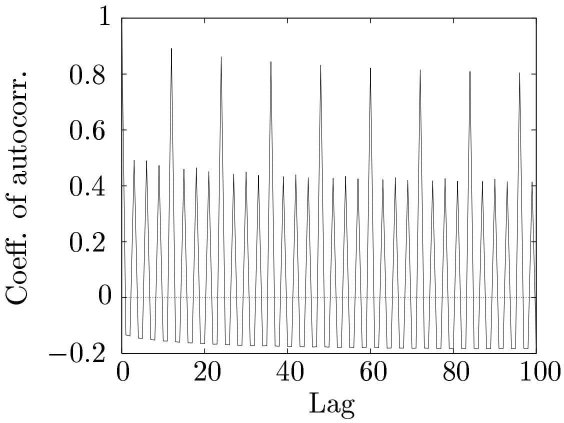

Figure 2: *Frame correlations*

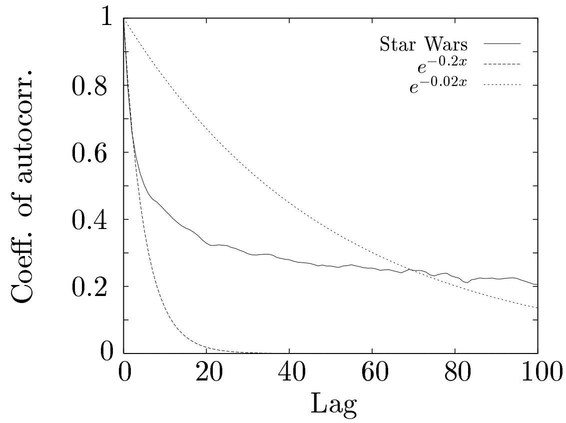

Figure 3: *GOP correlations*

3 Video modeling literature

A large variety of papers about video traffic modeling can be found in the current teletraffic literature. The modeling approaches can be divided into three main classes:

- Markov chains, e.g. [2, 9, 11]
- Autoregressive processes (including TES models), e.g. [6, 12, 13]
- Self-similar or fractal models, e.g. [1]

An overview on video models can be found in e.g. [4, 15]. Most of the papers deal with Markov chain approaches since the estimation of the model parameters is straightforward and there is a large number of analysis techniques available to examine queuing systems with this type of input. The main disadvantage of these models are the exponentially decaying autocorrelation functions of the generated sequences. This leads to inaccurate performance estimates if those are dependent on long-range correlation properties of the video sequence. As shown in this paper, only with some effort it is possible to obtain a Markov chain model whose generated sequence owns a high coefficient of autocorrelation even for larger lags.

Similarly to Markov chain models, autoregressive models suffer from the difficulty to approximate the autocorrelation function of empirical data sets. For more complex models the estimation of the model parameters and the queueing analysis techniques are often more difficult than in the Markov chain case.

Recently, a lot of attention was attracted by fractal modeling of traffic streams in communication networks. Up to now, most of the papers deal mainly with the statistical analysis of data sets, i.e. in most cases the estimation of the Hurst parameter of an empirical sequence, and provide only few information about traffic models and the analysis of queuing systems with fractal input sources.

To conclude this brief outline on video traffic models, we point out that all classes of models have their pros and cons, and that some care has to be taken what type of model is chosen for the analysis of a given communication system with respect to given performance measures like cell loss probabilities in multiplexers. In this study, we focus on Markov chain models of different complexity in order to examine the advantages and limitations of this comparatively simple model class.

4 Markov chain models

4.1 Layered video traffic modeling

From [14] we conclude that we can separate several layers of a MPEG video traffic stream in ATM systems:

- Sequence layer: the whole video sequence, several minutes to hours,
- Scene layer: Intervals where the content of the pictures is almost the same, several seconds,
- GOP layer: Period of one GOP, hundreds of milliseconds,
- Frame layer: Period of a single Frame, tens of milliseconds,
- Cell layer: Period of a single ATM cell, microseconds.

First, we have to decide which layer should be modeled by the Markov chain because it will be difficult to find a model which is able to cover all time scales mentioned above. For the cell loss simulations in Section 5 we need a sequence of frame sizes, which we can either generate directly or indirectly by generating higher layer sequences, which we divide into frames. We decided to model the GOP layer process for the following reasons.

When choosing the frame layer we have to model a periodic autocorrelation function as shown in Fig. 2 to obtain reasonable cell loss estimates for a large range of buffer sizes [16]. This can only be achieved with a Markov chain with a sufficiently large number of states. On the other hand, if we choose the sequence layer model we first have to determine a GOP size sequence and then to generate the frame sizes from this sequence. This adds a considerable amount of complexity to the model but it will also improve its long-range dependence behavior.

Before we present the three GOP size process models, we give an outline of the procedure which generates the frame sizes from the GOP sizes. First, we use an empirical video frame size trace to estimate the mean size of each frame of the GOP. If we divide the mean frame sizes by the mean GOP size, we receive a scaling factor for each frame of the GOP. To generate a sequence of frame sizes we use one of the models introduced later to generate the GOP sizes and compute the frame sizes by multiplying the GOP size with the scaling factors. As the results of this paper show this simple method leads to a good approximation of the frame process of the video trace. In particular, the periodic nature of the frame process is approximated with little effort. Due to the fact that both GOP and frame sizes of either type are often approximately Gamma distributed [14], this method also leads to frame size distributions which are close to the original ones. The only frame layer information which is lost consists of the frame by frame correlation besides the correlation which is induced by the GOP pattern. However, from recent work we conclude that this un-modeled piece of information has almost no influence on cell loss results [16].

In the following we will present three Markov chain models which are considered in this paper. The basic model structures of these models are taken from [17], [11], and [2], where these models are suggested to model the frame size process of VBR video traffic. We point out that the intended use of these models differs from the one of these studies in several aspects, like GOP instead of frame process, and other empirical data sets, other performance measures. Therefore, some care has to be taken in comparing the results of those papers and this study.

All models have in common, that their parameters are estimated from a descretized GOP size sequence. A GOP size sequence of length N is computed from the empirical MPEG trace by summing up the frames of each GOP. Next, the range of GOP size values is divided into fixed size, non-overlapping intervals. Each of these intervals relates to a state of the Markov chain. During GOP size generation, each time the Markov chain enters a state, a GOP size is generated, which is equal to the mean value of the GOP sizes which fall into the interval related to this state. Thus, all models generate GOP size sequences, where the number of different GOP sizes is equal to the number of states of the Markov chain.

4.2 Histogram model

The *Histogram model* is the most simple model for the GOP size process. We compute a GOP size histogram from the empirical data set, where the number of histogram bins is equal to the number of states of the Markov chain. The probability P_i to enter state i is equal to n_i/N, where n_i is the number of GOP sizes which fall into interval (or bin) i. The GOP process is generated by drawing samples according to the probability vector $\{P_i\}$. Strictly speaking, this is not an ordinary, i.e. first-order, Markov chain, where the current state depends on the last one, because in the *Histogram model* the current state is independent from any past states. This model fits into the Markov context, however, if we allow for a more general definition of kth-order Markov chains, where

$$\begin{aligned} &Prob(X_n = i_n | X_{n-1} = i_{n-1}, ..., X_0 = i_0) = \\ &\quad Prob(X_n = i_n | X_{n-1} = i_{n-1}, ..., X_{n-k} = i_{n-k}) \end{aligned} \tag{1}$$

X_n denotes the state of the Markov chain at time n.

Using this definition, the *Histogram model* consists of a 0th-order Markov chain.

Fig. 4 and 5 show a GOP and frame size trace generated by the *Histogram model*. This figures are shown for the sake of illustration and will not be used to compare the models. As expected, the Q-Q-plot (cf. Fig. 6) shows that the model provides a good estimate of

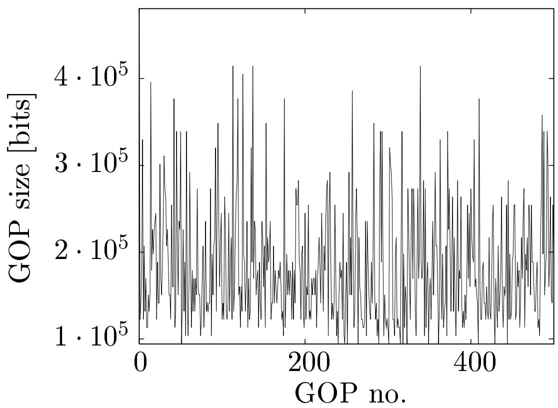

Figure 4: *Model GOP trace*

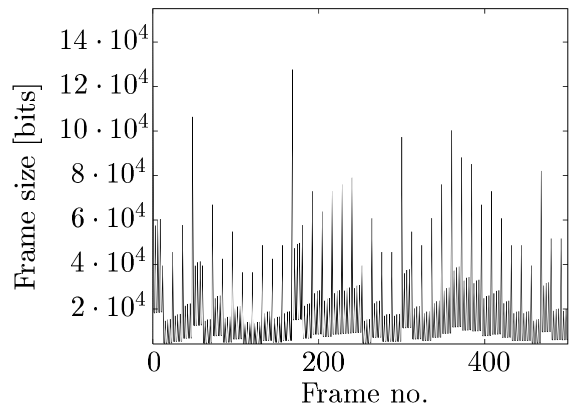

Figure 5: *Model frame trace*

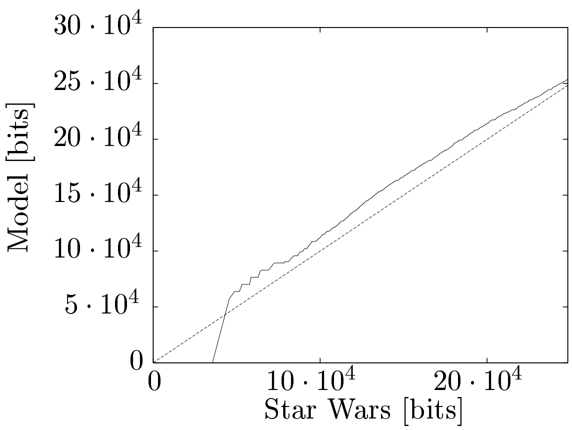

Figure 6: *Q–Q–plot*

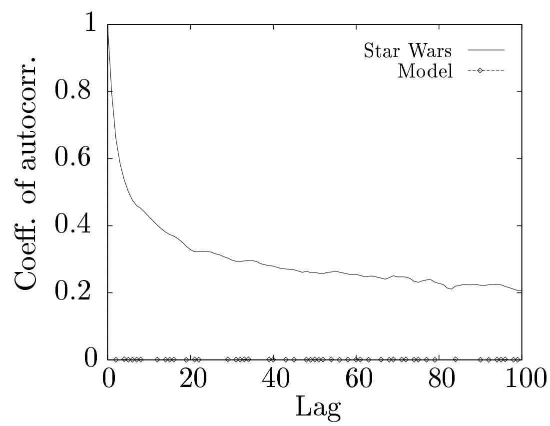

Figure 7: *Autocorrelation function*

the empirical GOP size distribution. The disadvantage of this model is the lack of any GOP correlation information (cf. Fig. 7).

4.3 Simple MC model

The *Simple MC (Markov Chain) model* consist of an ordinary 1st-order Markov chain. The number of states M is G_{max}/σ_G, where G_{max} denotes the size of the largest GOP and σ_G the standard deviation of the GOP sizes. Thus, the size of the quantization interval is σ_G. The entries of the transition probability matrix $\{P_{ij}\}$ are estimated by

$$P_{ij} = \frac{n_{ij}}{\sum\limits_{k=1}^{M} n_{ik}}, \tag{2}$$

where n_{ij} denotes the number of transitions from interval i to interval j.

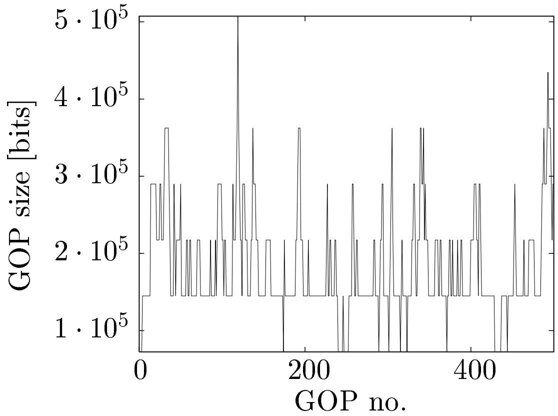

Figure 8: *Model GOP trace*

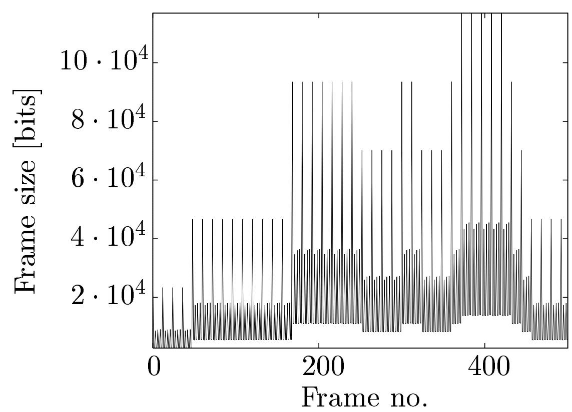

Figure 9: *Model frame trace*

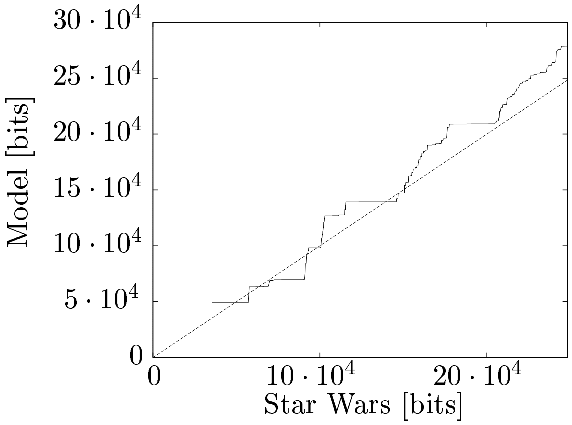

Figure 10: *Q–Q–plot*

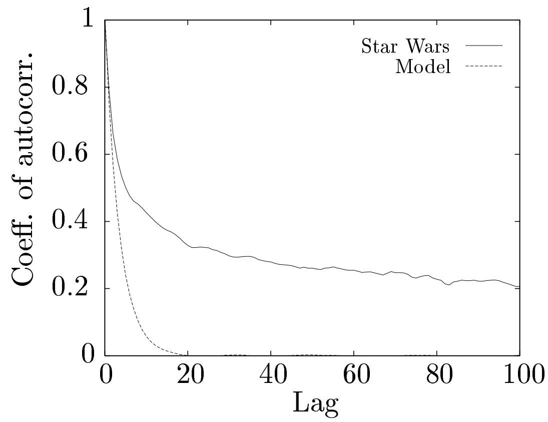

Figure 11: *Autocorrelation function*

This model includes the correlations from one GOP to the next one but no correlations over larger lags. This is also indicated by the exponentially decaying autocorrelation function.

Fig. 8 and 9 show a GOP and frame size trace generated by the *Simple MC model*. The estimate of the empirical GOP sizes is adequate (cf. Fig. 10), but the approximation of the autocorrelation function is bad (cf. Fig. 11) but better than that of the *Histogram model*.

4.4 Scene-oriented model

The *Scene-oriented model* consists of a Markov chain which is controlling the scene change process and a number of Markov chains, such as the *Simple MC model* type, which generate the GOP sequence for each scene class.

For the Markov chain generating the scene process we need to divide the GOP process into scenes. From statistical point of view, it is not necessary to determine the scene boundaries of the original video sequence by watching the movie. We prefer to use a method to find these boundaries which only depends on a few statistical parameters. These parameters should be available by simply scanning the GOP size sequence and without any knowledge of the content of the scenes. We suggest the following algorithm to find the scene boundaries. G_i denotes the size of GOP i and n the GOP number.

1. Set $n = 1$. Set current left scene boundary $b_{left} = 1$.
2. Increment n by 1. Compute the coefficient of variation c_{new} of the sequence $G_{b_{left}}$ to G_n.
3. Increment n by 1. Set $c_{old} = c_{new}$. Compute the coefficient of variation c_{new} of the sequence $G_{b_{left}}$ to G_n.
   (a) If $|c_{new} - c_{old}|(n - b_{left} + 1) > \epsilon$, set the right scene boundary $b_{right} = n - 1$ and the left scene boundary of the new scene $b_{left} = n$. Go to step 2.
   (b) If the above inequation does not hold go to step 3

Iterating this algorithm over the whole GOP sequence provides a series of scene boundary pairs. The value ϵ limits the amount of variation which is tolerated for one scene. If adding a new GOP to the current scene increases or decreases the variation too much a new scene is starting at this GOP number.

Next, we compute the mean GOP size of each scene. After defining the number of scene classes which is equal to the number of states N_s of the scene change Markov chain, we have to classify the scenes by means of their mean GOP sizes and to compute the transition probability matrix for the scene classes. This is done analogously to the procedure for the GOP sizes of the *Simple MC model*. It is important to note that the transition matrix is not simply based on the changes because of scene endings but on the GOP-by-GOP changes, i.e. if scene class i lasts five GOPs the four transitions from class i to i have also to be counted. This is done to obtain the same average scene lengths as the empirical sequence.

After creating the transition probability matrix of the scene change process, the matrices for the GOP process of each scene class have to be computed. We concatenate all GOP sizes of the scenes belonging to the same scene class in the order of their appearance and use the method of the *Simple MC model* to estimate the N_s transition matrices including the GOP sizes which are related to their states.

The GOP generation process of the *Scene-oriented model* for a simulation works as follows. First, the new state of the scene change Markov chain is determined. If the state or scene class does not change we keep on using the same GOP generation Markov chain as before and compute the current GOP size based on the last one. If the scene class changes we determine the adequate GOP Markov chain and select the starting state at random.

Fig. 12 shows a summary of the parameter estimation procedure and the GOP size generation process for the *Scene-oriented model*.

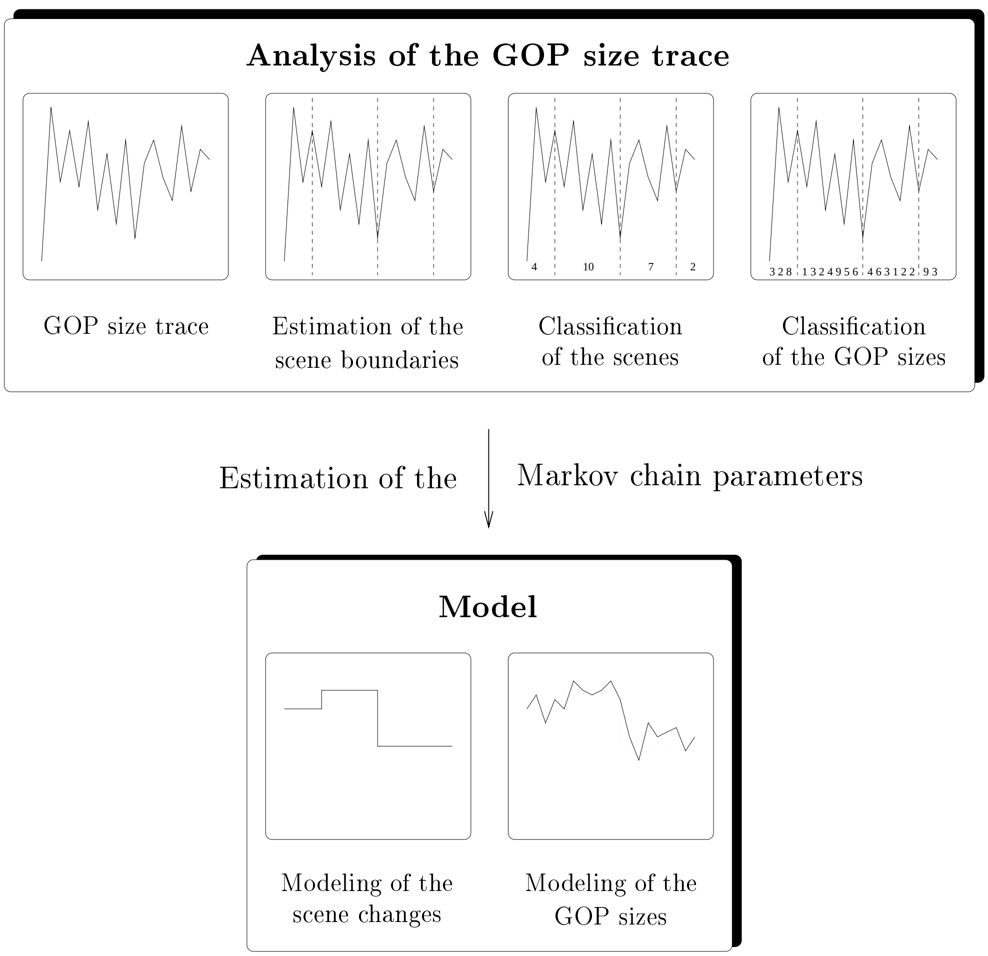

Figure 12: *Parameter estimation for the Scene-oriented model*

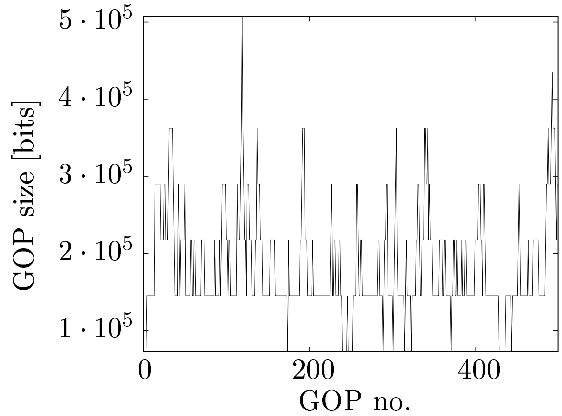

Figure 13: *Model GOP trace*

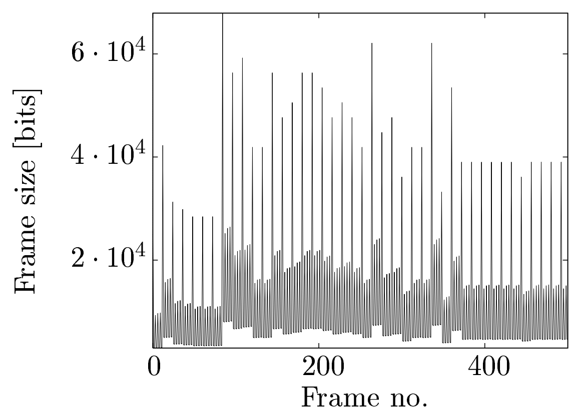

Figure 14: *Model frame trace*

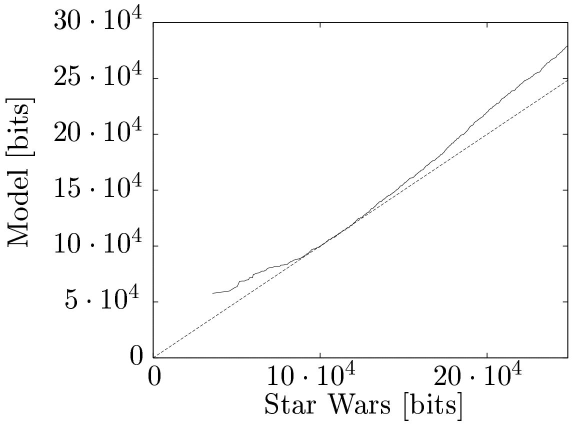

Figure 15: *Q–Q–plot*

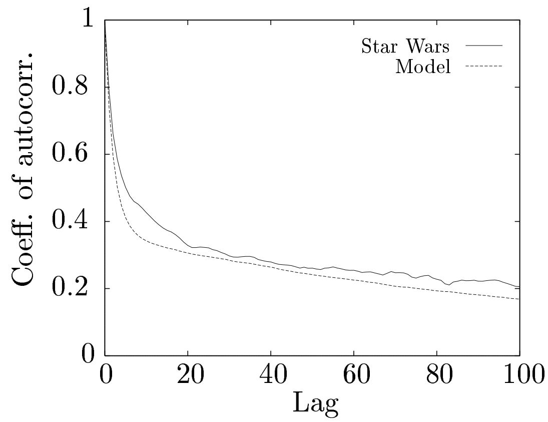

Figure 16: *Autocorrelation function*

For an analysis, the transition matrix of the nested Markov chains can be estimated by elementary matrix operations. Unfortunately, this already leads to very large matrices, which only describe one MPEG traffic source. If a superposition of sources has to be modeled for an analysis, simpler models should be considered.

Fig. 13 and 14 show a GOP and frame size trace generated by the *Scene-oriented model*. The estimate of the empirical GOP sizes is good (Fig. 15), and the approximation of the autocorrelation function is very good for the range of lags shown in Fig. 16.

Comparing the plots of the three models leads to the conclusion that the most complex model, the *Scene-oriented model*, shows very good agreement with the empirical data sets, whereas the the simpler models are unable to model the correlation behavior of the data sets over a larger period of time. In the next section, we will examine how these properties affect the capabilities of the models if they are used to predict cell losses at an ATM multiplexer buffer with VBR MPEG video input.

5 Cell loss simulation results

In this section, we present the cell loss simulation results which are used to compare the three models. For the simulation, we used a *fluid flow* approach, i.e. we simulated on frame level assuming a constant transmission rate of a video source for each frame. The frame level results are essentially equal to the cell level results if we assume that each video source spaces the cells of one frame over the frame duration.

The multiplexer has a link rate of 10 Mbps and buffer sizes of 100, 1000, 10,000, and 100,000 cells were considered and the multiplexer load is determined by the number of video input sources. We scaled down the link rate to 10 Mbps because we wanted to obtain realistic cell loss results in spite of the fact that the empirical data set has a bit rate of only about 5 to 10 % of high quality full-screen MPEG video sequences.

Fig. 17 shows the cell loss results for the three models and the *Star Wars* data set for a buffer size of 100 cells. The *Scene-oriented* and the *Simple MC model* show almost the same good approximation quality, but the *Histogram model* is performing only slightly worse. For the sake of clarity, in Fig. 18, 19, and 19 we do not show the curve for the *Simple MC model* because it is very close to the *Histogram model* curve.

Increasing the buffer size to 1000 cells (cf. Fig. 18) and correspondingly increasing the influence of correlations on the cell loss estimates shows that the *Scene-oriented model* still shows the best approximation quality, whereas the estimates of the simpler model are becoming more and more optimistic. However, for dimensioning purposes the simpler *Histogram model* might still be useful up to buffer sizes of 1000 cells. Only for very large buffer sizes of 10,000 cells (cf. Fig. 19) or 100,000 cells (cf. Fig. 20) the *Scene-oriented model* is substantially better than the simple model. Moreover, for network dimensioning purposes it is more convenient to use a model which behaves worse than the real traffic. This is clearly the case for the *Scene-oriented model* which overestimates the cell losses for larger buffer sizes.

These results show that only for buffer sizes which are rather large it is necessary to use scene level correlation information to obtain good cell loss estimates. In addition, the simulation results prove that the simple procedure to obtain the frame sizes by multiplying

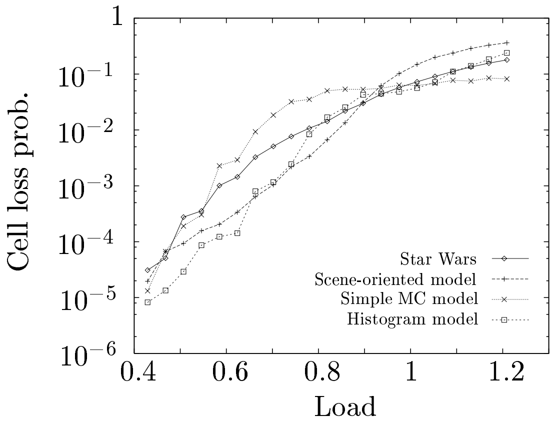

Figure 17: *Loss for 100 cells buffered*

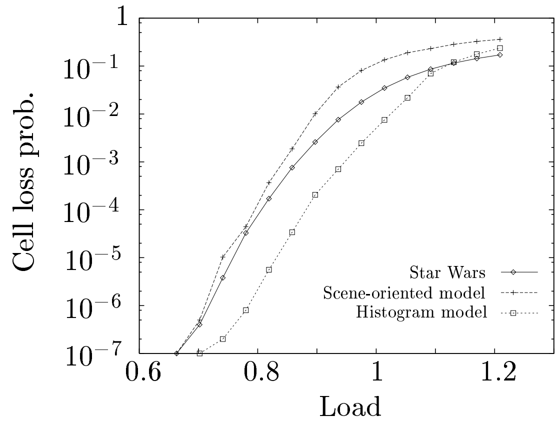

Figure 18: *Loss for 1000 cells buffered*

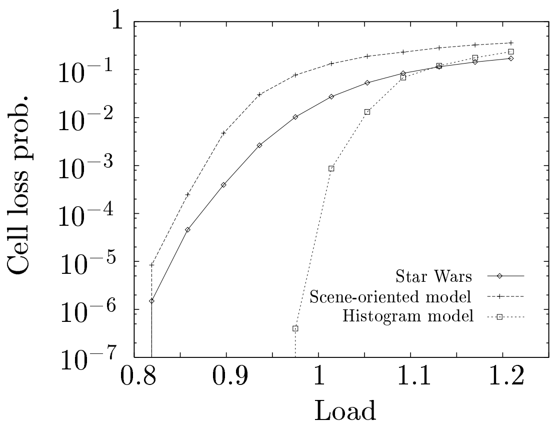

Figure 19: *Loss for 10,000 cells buffered*

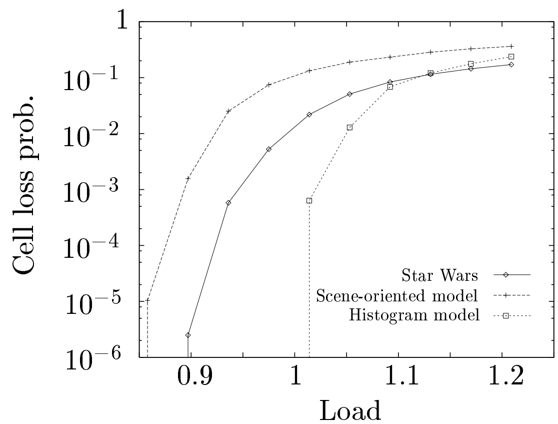

Figure 20: *Loss for 100,000 cells buffered*

scaling factors to the GOP sizes is a useful way to generate the frame sequence.

6 Higher-order Markov chains

The results presented in the last two sections show that an improvement in the correlation behavior and, correspondingly, the capability to predict cell losses for rather large buffers lead to the use of a complex model. It would be helpful to find a Markovian model which is more powerful than the *Histogram model* or the *Simple MC model* but still simpler than the Scene-oriented model. The straightforward approach is to avoid the use of scene-level information and to increase the Markovian order of the model until it shows an appropriate correlation behavior. Unfortunately, this approach has two important drawbacks.

First, we consider the number of model parameters and their estimation. In our case, the most important set of parameters of the Markov chain is the size of transition probability matrix. The number of elements of this matrix for a M-state Markov chain is $M^{order+1}$, if we do not consider elements which are definitely zero. M, however, should not be chosen too small because it determines the approximation quality of the marginal distribution of the data set. This will cause memory problems for orders larger than 10. Another problem is to obtain statistically significant estimates for the transition probabilities, because with an increasing order the number of samples for each estimate is very small even if we use very long empirical data sets.

After this more technical drawback, the properties of higher order Markov models both from autocorrelation function and coding theoretical point of view are evaluated. A first bit of insight we receive from Fig. 21 which shows the autocorrelation function of the *Star Wars* GOP sequence and some higher-order Markov chains models of it. As already mentioned, the decay of the empirical curve is clearly not exponential and increasing the orders of the Markov chains leads only to marginal improvements in the approximation quality.

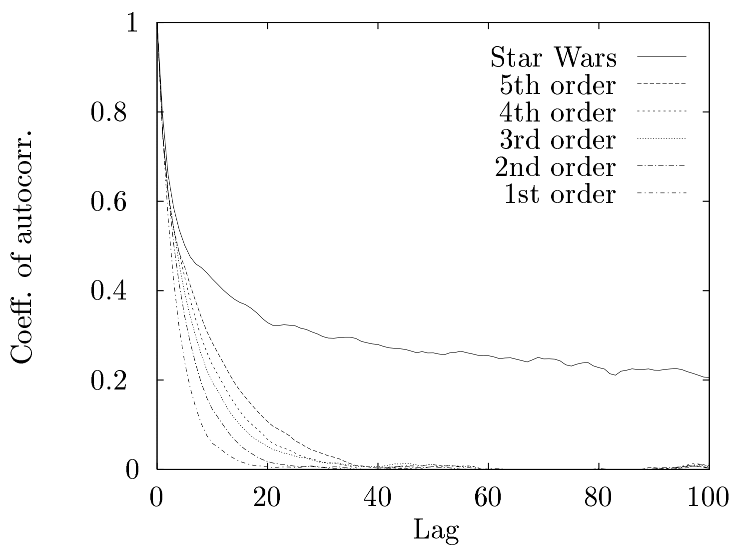

Figure 21: *Autocorrelation function of kth-order Markov chains*

In coding theory, the empirical entropy of a time series is used to determine the Markovian order of its generation process. The method we used can be found in [10]. In the following we will only present the results of the algorithm and their interpretation. The presentation of the algorithm is beyond the scope of this paper.

Fig. 22 shows the empirical entropies for Markov chains up to the order of 10 with 8,

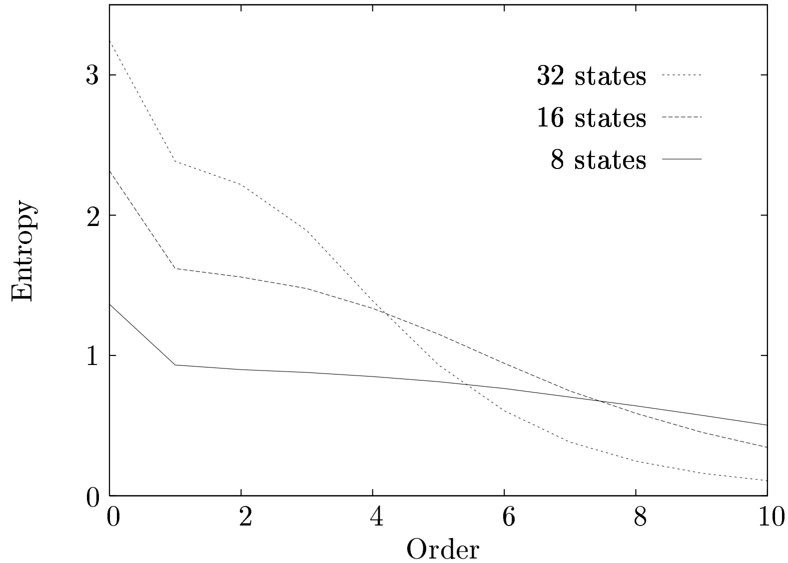

Figure 22: *Empirical entropy of kth-order Markov chains*

16, and 32 states. An entropy of 0 is equivalent to the fact that the model contains all properties of the empirical data set. From the curves, we conclude that there is a gain in model quality if we increase the order of the model. However, to obtain good models for 16 or 32 states it seems that the order should be larger than 5, i.e. at least one million matrix elements in the 16 states case. On the other hand, if we consider 8 states, there is almost no improvement for Markov chains with an order larger than 1. Even for an order of 10 the entropy is still rather high. Of course, the empirical entropy will also decrease to zero but only for large orders.

To sum up, both from technical and statistical viewpoint it is almost impossible to improve the correlation behavior of the Markov chain models by simply increasing the Markovian order of the model.

7 Conclusions

In this paper, we discussed three Markov chain models for the modeling of VBR MPEG video traffic with respect to their applicability for performance evaluation. The *Histogram model* consisted of a 0th-order Markov chain, the *Simple MC model* of a 1st-order Markov chain, and the *Scene-oriented model* of several nested Markov chains. These models were used to generate the GOP size process of an MPEG video source.

Only the most complex *Scene-oriented model* was able to model both the GOP size distributions and the autocorrelation function of the empirical *Star Wars* data set in an adequate way. The simpler models suffered from their bad approximation quality of the correlations. The capability of modeling long-term correlations had also an influence on the quality of the model estimates of the cell loss probabilities of an ATM multiplexer with MPEG video input. However, this only affected the estimation quality considerably for very large buffers (100,000 cells). The complex *Scene-oriented model* results was closest to the empirical data results in all cases considered, but for realistic buffer sizes (100 cells and 1000 cells) all models showed a good performance.

As an alternative to the *Scene-oriented model* the use of higher-order Markov chain models was considered. However, the discussion of autocorrelation curves of these models and of some empirical entropy properties show that this type of models is not applicable for practical purposes.

The results of this study show that Markov chain models can be used to generate VBR MPEG video traffic in view of the following constraints. These models should be used to model the GOP generation process rather than the frame process to avoid its periodic autocorrelation function. For systems where the performance parameters are affected by the correlation properties of the video traffic, the scene process should also be considered when modeling the GOP process.

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