Allocation of IPTV Streams over Broadband Wireless through Fuzzy Logic Control

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Abstract

IPTV video services are under development for broadband networks, with final hop delivery across a wireless link. Within these networks, dedicated sub-channels transport different types of traffic (video, voice, data…).. This paper proposes fuzzy logic control (FLC) to allocate video streams within an IPTV sub-channel subject to fluctuating available bandwidth. The method employs spatial and temporal complexity metrics to judge the appropriate share of available bandwidth, taking account of genre and dynamic coding rate fluctuations. So that the video sources can adjust their rates to the likely available bandwidth across the wireless link, reliable prediction of available bandwidth over time is also proposed. In tests, the FLC, which serves to merge the spatial and temporal metrics into a single control output, results in an overall gain in video quality over static equal allocation of bandwidth and also compensates streams that would otherwise suffer from an inadequate or alternatively an unnecessarily large bandwidth share.

1. Introduction

IPTV services are in active commercial development for converged Internet Protocol (IP) telephony networks, such as British Telecom's 21CN or the all-IP network of KPN in the Netherlands, with IP framing but low-blocking probability switching. Such networks are constructed with multimedia in mind [1], as only these applications can exploit their bandwidth capacity. Within the 21CN, video streaming is sourced either from proprietary servers or from an external Internet connection. However, when the video streams leave the core network they may well be delivered across their final hop by some form of broadband wireless such as IEEE 802.16 (WiMAX) or 3GPP Long Term Evolution (LTE). Available bandwidth varies over time due to the arrival of other types of traffic (peer-to-peer file download, web pages, voice) sharing the channel, yet video quality should be maintained across the video streams to avoid customer disappointment.

Fortunately, the compressed video streams forming the IPTV sub-channel will not necessarily have the same bandwidth requirements, as their spatial and temporal complexity will vary, resulting in differing coding complexities. In the long term, this variation is determined by the video genre, such as sport, cartoon, soap, and so on but there are also changes over time caused by such factors as the type of frame and whether there is a shot change or a scene cut. Consequently, multiple video streams sharing the sub-channel can each be dynamically allocated a proportion of the available bandwidth according to their coding complexity.

The contribution of this paper is to present a complete system for bandwidth allocation of coexisting IPTV streams within a multimedia sub-channel. Prior work has mainly been concerned with conventionally broadcast TV and has unrealistically concentrated on statistical multiplexing of Variable Bit-Rate (VBR) streams rather than the Constant Bit Rate (CBR) streams favored by industry. Rate allocation has mainly been on the basis of spatial complexity, whereas in this paper temporal complexity is also included. The translation of spatial and temporal complexity into bandwidth needs is an uncertain or imprecise process, suggesting that fuzzy logic control (FLC) is suited to this task. FLC for video applications has gained acceptance [2] for congestion control and rate control.

In the paper, the changing available bandwidth is represented by a four-state Markov chain. A linear predictive filter (LPF) [3] estimates the likely available bandwidth based on monitoring the history of prior availability of bandwidth to the IPTV sub-channel. It is important to realize that in our experiments the wireless channel is not modeled directly by the four-state Markov model. Rather the available bandwidth resulting from the arrival of other traffic sharing the wireless link is modeled. Too rapid changes in the allocation of the available bandwidth share by the FLC are avoided in order not to cause an unsettling

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subjective effect for the viewer when the matched video streams are adjusted to the allocation. Adjusting the bandwidth share based on an average of past spatial and temporal complexity also overcomes possible signaling latency in adjustment of the video streams' allocation within the IPTV sub-channel.

Allocating bandwidth to video streams simply on the basis of efficient usage and fair distribution of bandwidth, for example [4], is not necessarily wise, because the delivered video quality of some video streams will be more affected by a reduction in bandwidth than by others. Both unwarranted degradation of quality and unnecessarily high quality of video may take place. A further weakness of statistical allocation for variable bit-rate video is that such approaches are not appropriate if the input data-rates have high variances. Smoothing of the date-rates may be applied but this can affect latencies. The goal of our work is to adjust the relative quality ranking of the sequences over time to equalize their delivered video quality to fall within an acceptable range.

2. Background

Video stream bandwidth allocation has some affinity to statistical multiplexing except that rather than output compressed VBR video streams to a common buffer, the rate of CBR streams is varied according to the available bandwidth. The resulting stream segments remain CBR until the next allocation decision point and each video stream as a whole appears as a set of CBR segments, in effect the streams are semi-VBR.

In [5], bandwidth allocations between CBR streams at GOP boundaries occurred, with a refinement to include scene change boundaries. Joint control through complexity statistics (spatial only) was also applied to a set of rate-Distortion (R-D) controlled video encoders (for MPEG-2 before rate-distortion was built in to the encoder). Only spatial complexity was considered and, therefore, no control was applied to merge temporal complexity, at a cost in accuracy. Alternatively, it is also possible to predict complexity prior to encoding [6], though this method apart from its complexity cannot be adapted to bitrate transcoding of pre-encoded video. Also for live encoders only, an alternative is to partially decode future frames, as occurs in [7]. Unfortunately in [7], only the temporal complexity measure is found by partial decoding, while spatial complexity is predicted from a previous frame. In our paper, for computational reasons, we adopt a simpler form of video complexity measure, which has the advantage that real-time operation is guaranteed.

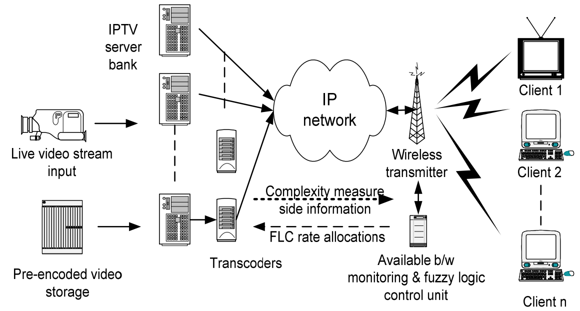


Figure 1. IPTV streams over a broadband network with fuzzy logic control.

3. Methodology

A top-level system diagram is presented in Fig. 1. Video stream input is either from live video streams, such as from a sporting event, or from pre-encoded video, possibly adapted for TV display. Depending on the predicted available bandwidth determined by the LPF, the rate at the servers is allocated by the FLC unit. This takes place at the point of distribution of individual video streams across the shared wireless channel. Once the FLC has determined the proportions allocated to each video stream sharing the IPTV sub-channel, the video bitstream rates are adjusted either by bitrate transcoders or, if live video, by direct adjustment of the quantization parameter. Therefore, a feedback channel is required that relays the desired video output levels from the monitoring point at the wireless transmitter, where the FLC is based, back to the encoders/transcoders.

The video complexity data are calculated (or pre-calculated in the case of pre-encoded video) and sent along with the compressed video as cross-layer side information to the FLC. (There also exist complexity measures that can be derived in the compressed domain [8], avoiding the need to send side information.) To compensate for possible latency in signaling of rate adaptation through the feedback channel, decision points are currently every 1000 frames (or 40s at 25 frames) based on an average of the frame-by-frame allocations by the FLC, whereas the predicted available bandwidth is found every 2 s.

3.1. Video complexity measurement

In [9], for the purpose of selection of suitable video sequences for subjective testing, two measures were provided for judging the spatial information (SI) and temporal information (TI). For the spatial measure, the pixel luminance values within each frame under test are Sobel filtered. Subsequently, the standard deviation

(SD) of the Sobel per-pixel output (the norm of the gradient) is taken to form the SI of that frame. For the temporal measure, the difference in luminance value between the current frame and the previous one for each pixel is computed. The per-frame SD of these differences is then taken to form the TI. (The ITU recommendation for subjective testing is to take the maximum of the SDs for the frames of a complete video sequence but we select the per frame SDs themselves, as our purpose is different.)

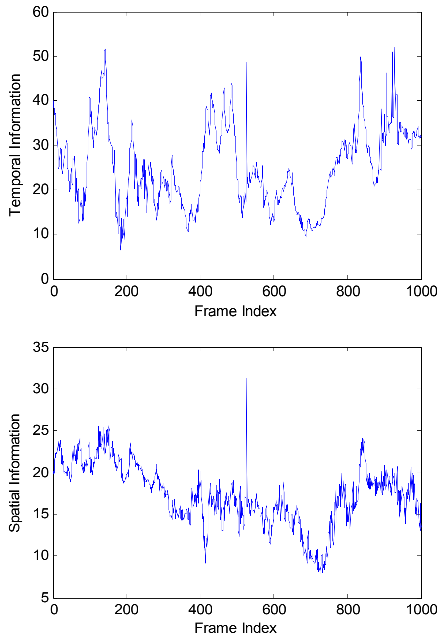
To test a variety of video sequences, six 15-minute sequences each of a different genre type were selected as the client streams. The variable bitrate sequences were MPEG-2 encoded at 25 frame/s with a target rate (before transcoding) of 1.5 Mbps, with GOP parameters M=3, N=15. The MPEG-2 codec was selected as the Digital Video Broadcasting consortium and other major providers employ it for video delivery.

Six clips of different genre were selected: 1) Football — TV sports footage; 2) Friends — the well-known situational comedy; 3) Top Gear — a UK TV car magazine program; 4) Pop Musical; 5) Cartoon; and 6) the film ‘Titanic’. Fig. 2 plots TI and SI for a representative 1000 frame sequence taken from two of the sequences, sampled for each frame. (Shortage of space prevents inclusion of plots for all six sequences, though all six had different characteristics). The TI varies in the level of information, which is higher for a sequence such as Football with significant motion activity by the players. On the other hand, Cartoon is characterized by a low level of activity over time (with activity confined to (say) lip movement) but its SI is high. There are also frequent spikes in the cartoon TI caused presumably by scene changes. The SI metric is particularly relevant to Intra-coded frames, as these only employ spatial coding, resulting in higher bit-rates when these occur, whereas the SI and TI are relevant to predictively coded frame types within a GOP. The implication is that both metrics are needed for allocation of bandwidth.

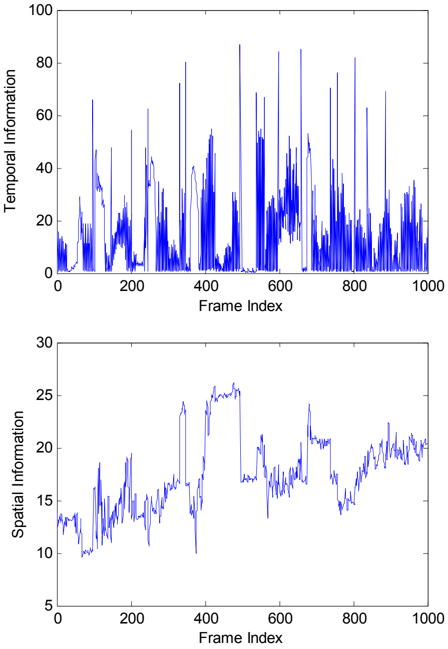
Because of the volatility of both SI and TI, for our purposes frame-by-frame sampling is needed rather than employ a summary statistic for the whole sequence. The TI and SI measurements, after normalization, form the input to the fuzzy models on a per video stream basis.

3.2 Fuzzy logic control

The inputs to the FLC on a per video basis are the two complexity measures, TI and SI, which are used to determine the sub-channel allocation of any one video stream.



(a) Football (Sport)



(b) Cartoon

Figure 2. Sample 1000 frame sequences showing per frame ITU temporal and spatial information [9] for two different genre examples.

The TI and SI inputs to the fuzzy models are first normalized by dividing by the largest value of TI and

SI respectively for the set of samples from each of the current frames of all video streams sharing the sub-channel.

The fuzzy models for inputs TI and SI were a number of overlapping triangular membership functions. Space does not permit the reproduction of these models in this paper. Though triangular membership functions result in a loss of smoothness they allow rapid calculation of output, possibly with a hardware unit. The inputs were combined according to the common Mamdani inference method to produce the output values from triangular output membership functions similar to those of the input models, according the rule set given in Table 1. For example, if TI is ‘high’ and SI is ‘medium’ then output is ‘high’. The membership value of the output in the ‘high’ output subset is determined by inference method. Subsequently, the standard center of gravity method was employed to resolve to a crisp output value, which expresses a proportion of the available bandwidth.The FLC’s behaviour itself was examined through Matlab Fuzzy Toolbox v. 2.2.4.

The behaviour can be predicted from its output surface, Fig. 3, formed by knowledge of its rule table and the method of defuzzification. Matlab’s toolbox allows a set of output data points to be calculated to a given resolution, allowing interpolation of the surface. By means of a look-up-table derived from the surface, a simple hardware implementation becomes possible. From Fig. 3 it is intuitively apparent that transitions between the output prediction states are smooth and that approximately equal weight is given to the two inputs from the symmetry of the output surface.

The crisp outputs formed by repeated application of the fuzzy logic models to the SI and TI inputs of each video stream results in a control value for each video stream. These control values are converted to fractions of the available bandwidth by division of each by the total of the output values. An average is subsequently taken over an epoch of 1000 frames. The average forms the control signal to the transcoder (or live video encoder) to adjust the bandwidth share for a particular video stream over the next 1000 frames (or 40 s). The FLC’s output is a normalized proportion of the available bandwidth. The predicted available bandwidth must also be formed at the transcoder subject to a prediction of available bandwidth, which changes every 2 s.

3.3 Predicting available bandwidth

Available bandwidth for the IPTV sub-channel is predicted by a P-order LPF [3], with an order eight filter. The P-order LPF prediction filter is represented by

Table 1. FLC If..then rules used to identify output fuzzy subsets from inputs.

		TI				
SI		*Very Low*	*Low*	*Medium*	*High*	*Very High*
	Very low	Very low	Very low	Low	Low	Medium
	Low	Very low	Low	Low	Medium	Medium
	Medium	Low	Medium	Medium	High	High
	High	Medium	Medium	High	High	Very High
	Very high	Medium	High	High	Very High	Very High

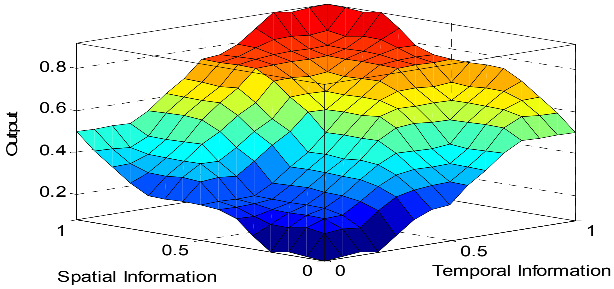


Figure 3. Output surface giving the available bandwidth proportion for any one video stream.

$$X(m+1) = \sum_{k=1}^{P} w_k . X(m-k+1) , \qquad (1)$$

where $X(m+1)$ is the predicted available bandwidth of the IPTV sub-channel, estimated from P previous monitored values of available bandwidth over sample instances m, while the w_k are the P adaptive filter weights indexed by k. The weights are estimated through (2):

$$\mathbf{w}(m+1) = \mathbf{w}(m) + \frac{e(m).\mathbf{X}(m)}{\|\mathbf{X}(m)\|^2}, \qquad (2)$$

where $\mathbf{w}$ is the length P column vector of weights and $\mathbf{X}$ is a length P column vector of available bandwidth measurements over time, as in (3).

$$\mathbf{X}(m) = [X(m), X(m-1), \dots , X(m-P+1)]^T \; (3)$$

when T represents the vector transpose. The variable $e(m)$ is the error between the monitored and the previously predicted available bandwidth value.

3.4 Available bandwidth model

A four-state Markov chain modeled the available bandwidth in the sub-channel over time. In [10], the underlying wireless channel capacity is modeled by a multi-state Markov chain leading to a determination of the effective bandwidth. In our model, each state was directly reachable from every other state. The mean available bandwidth in state 1, 2, 3, and 4 was set to 1, 2, 3, 4 Mbps respectively for testing purposes only. Each state on average was maintained for 2 s, equivalent to 2000 monitoring points. If Ts=2000 then the probability of being in any one state is:

$$P_s = 1 - \frac{1}{T_s} = 0.9995 \qquad (4)$$

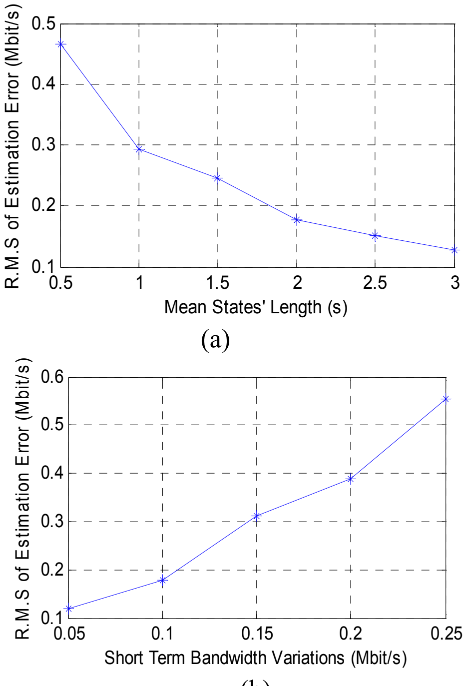
and given that the probability of going to any other of three states is equi-probable and equal to (1-0.9995)/3 the state transition matrix is:

$$\begin{bmatrix} 0.9995 & 1.66\times10^{-4} & 1.66\times10^{-4} & 1.66\times10^{-4} \\ 1.66\times10^{-4} & 0.9995 & 1.66\times10^{-4} & 1.66\times10^{-4} \\ 1.66\times10^{-4} & 1.66\times10^{-4} & 0.9995 & 1.66\times10^{-4} \\ 1.66\times10^{-4} & 1.66\times10^{-4} & 1.66\times10^{-4} & 0.9995 \end{bmatrix} \qquad (5)$$

In the model of available bandwidth it is supposed that perturbations occur to the mean available bandwidth in any one state. To generate the amplitude of the perturbation, samples were taken from a symmetrical Uniform distribution.

4. Results

The ability of the LPF to predict the sub-channel available bandwidth was tested in order to demonstrate the feasibility of predicting a changing available bandwidth in this way. From Fig. 4 with each data point representing fifty tests, the accuracy of the LPF improves in a quasi-linear manner with increasing sampling period and equally the prediction reliability degrades with increasing short term perturbations. The LPF sampling rate was previously heuristically determined, though there is also scope for optimization of this rate. Estimation error was found by comparing each prediction of the LPF with the matching available bandwidth subsequently generated by the available bandwidth model of Section 3.4. In the tests, the LPF was run in a regime where the amplitude of the perturbations was set to 0.1 Mbps and, as previously mentioned, with a sampling epoch of 2 s, thus ensuring the Root Mean Square (RMS) error is less than 0.2. A useful future addition to the procedure would be to include a measurement noise model to account for possible measurement inaccuracies.



(a)

(b)

Figure 4. Root Mean Square (RMS) error in LPF tracking of (a) the mean state according to duration b) according to short-term available bandwidth amplitude variation.

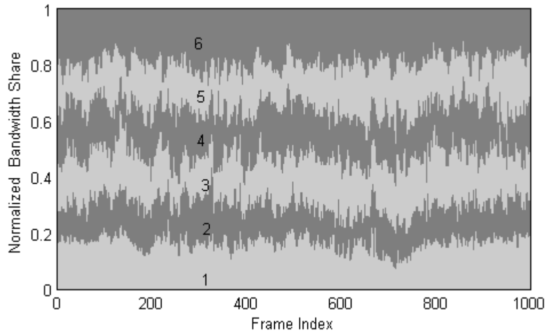


Figure 5. Sample 1000 frames of bandwidth allocation through the FLC for the sample video streams with 1 corresponding to Football and 6 to Titanic.

Simulations were run, averaged over fifty trials, to find the bandwidth allocation according to the TI andSI metrics applied to the FLC inputs. Fig. 5 shows an illustrative sample of 1000 frames of frame-by-frame allocation by the FLC for the sources of Section 3.1. Of course, the allocation is not changed for every frame but, as mentioned in Section 3, is averaged over

1000 frames to account for signaling latency. In Fig. 6, the average available bandwidth share allocations for the six video streams are shown in normalized form for the same sample of 1000 frames in Fig. 5. A share of exactly one represents exactly one sixth of the available bandwidth as it changes over the course of the 15 min. simulated. It will be seen that, because of their relative complexity, some streams such as Friends are allocated less than an equal share, whereas others such as Football exceed an equal share. By examining the relative Peak Signal-to-Noise Ratios (PSNRs) on a stream-by-stream basis, Fig. 7, then it is apparent that Football is compensated for poor quality that would result from an equal share allocation, whereas the other streams suffer little if not at all by this over allocation. This is because the quality of other streams is already good and does not suffer from an under allocation of available bandwidth.

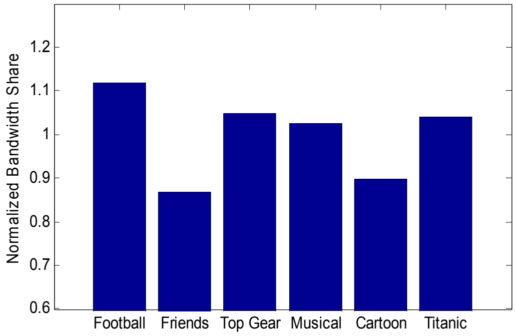


Figure 6. The average bandwidth share allocated over the period of Fig. 5.

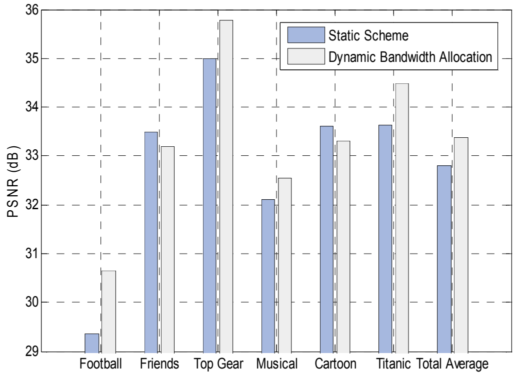


Figure 7. Video quality (Y-PSNR) over 15 minutes by an equal allocation static scheme and the FLC dynamic control of available bandwidth allocation.

5. Conclusions

Two forms of prediction have been deployed in this paper to rate adjust video streams sharing a multimedia sub-channel. Firstly, the proportion of the available bandwidth to be allocated to each video stream is determined by a fuzzy logic control unit, which makes its decision on the basis of each video's coding complexity. Secondly, the overall available bandwidth that can be assumed to be available to the video sources is predicted by a linear prediction filter with a bounded prediction error. Fuzzy logic control effectively combines both spatial and temporal video complexity measures. The system avoids over-allocation of bandwidth to video sources whose coding complexity does not warrant it but dynamically allocates bandwidth to those sources whose quality would otherwise suffer. Future work will involve comparing the simulated available bandwidth of the multimedia sub-channel with channel traces obtained in a realistic setting. We also intend to examine compression domain complexity measures.

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