Statistical multiplexing of distributed video streams

Nesrine Changuel, Bessem Sayadi, Michel Kieffer

Statistical multiplexing of distributed video streams

Nesrine CHANGUEL[1], Bessem SAYADI[1], Michel KIEFFER[2,3]

[1]Alcatel-Lucent - Bell-Labs Villarceaux, France

[2]L2S, CNRS - SUPELEC - Univ Paris-Sud, F-91192 Gif-sur-Yvette

[3]LTCI, CNRS-Télécom ParisTech, F-75013 Paris

Nesrine.changuel@alcatel-lucent.fr, Bessem.sayadi@alcatel-lucent.fr
Michel.Kieffer@lss-supelec.fr

Résumé – Nous considérons un élément du réseau sensible au contenu multimédia fourni par plusieurs serveurs. Son rôle est de stocker le contenu vidéo encodé et le multiplexer pour être diffusé sur une liaison sans fil. Nous proposons une technique de contrôle décentralisée capable de satisfaire une contrainte d'équité en qualité vidéo entre les programmes. Contrairement à la plupart des systèmes de multiplexage statistique, notre système est en partie décentralisé. L'allocation de bande passante entre les programmes est centralisée et faite dans le réseau en prenant en compte la contrainte de l'équité en qualité. Chaque serveur vidéo est contrôlé indépendamment des autres, ne nécessitant aucun échange avec les autres serveurs. Le système de contrôle de l'allocation de bande renvoie aux serveurs vidéo le niveau de remplissage de la mémoire tampon à laquelle il est associé. Les encodeurs utilisent ces retours d'information pour adapter leurs compromis débit-distorsion pour que la mémoire tampon atteigne un certain niveau de remplissage référence. Les résultats expérimentaux montrent que, dans le cas de sources Gaussiennes, un équilibre est atteint, et que la contrainte de l'équité de la qualité est satisfaite.

Abstract – We consider a media aware network element (MANE) fed by several remote video servers. The role of the MANE is to bufferize the encoded video contents and to build a multiplex containing all video programs to be broadcasted or multicasted over a wireless link. We design a decentralized control technique able to satisfy some video quality fairness constraint among programs. Unlike most statistical multiplexing systems, our scheme is partly decentralized. The bandwidth allocation among programs is centralized and done within the MANE, but takes into account the quality fairness constraint. Each video server is controlled independently from the others, requiring no exchange between servers. The MANE feds back to each video server the level of its associated buffer to help the remote video servers to adapt their rate-distorsion trade-off so that the buffer reaches some reference level. Experimental results show that in the case of Gaussian sources, compressed and delivered to the MANE, an equilibrium is reached, and that the fairness constraint is satisfied.

1 Introduction

In multimedia broadcasting systems, multiple video services are transmitted over a fixed bandwidth channel. Therefore, the data rates required by these multimedia services are expected to vary over a wide range, depending on their multimedia content.

Statistical multiplexing of compressed video signals consists in adapting jointly the rate and the distortion of the encoded video to use the available bandwidth in an optimal way. Usually, Variable Bit Rate (VBR) [1] video coders are used in order to satisfy several constraints linked to the quality of the encoded streams [2, 3] and to the transmission delay [4, 5]. The video quality fairness is an essential constraint that should be considered in the statistical multiplexing system in order to provide programs with quality levels of the same order of magnitude.

When considering a statistical multiplexer of H.264/AVC-encoded video, the rate-distortion (R-D) control may be performed by adjusting dynamically the encoding parameters of the source coders as in [5]. This may also be performed by re-encoding or transcoding the encoded video to match the R-D target fixed by the control scheme. With H.264/SVC, the encoded streams are organized into quality layers and the number of transmitted layers for each frame may be adjusted [6, 7]. In both cases, to satisfy video quality fairness among programs, it is necessary to share quality information between encoders, transcoders, or layer filtering units. Since video servers are usually located in separate places, this may introduce some communication delays. Therefore, a decentralized rate control scheme is desirable. The problem of rate control, buffer management and video quality control for video streaming system is addressed in [8, 9]. The video streaming problem is considered by jointly controlling the encoder rate and the network congestion. The control system is formulated via a feedback control system using first a Proportional and second a Proportional-Integral (PI) controller. The robustness and the stability of the proposed control-theoretic approach are derived.

In this paper, we consider a media aware network element (MANE) fed by several remote digital media servers. The MANE is in charge of buffering the encoded streams and to build a centralized bandwidth allocation among programs. It takes into account quality information provided by each video coder to try to satisfy the fairness constraint. Each video server is controlled independently from the others, requiring no exchange between servers. The MANE feeds back to each video server the level of its associated buffer to help the remote video servers adapt their R-D trade-off so that the buffer within the MANE reaches some reference level. We adopt a control-theoretic approach that performs rate allocation via a feedback control system. In the case of Gaussian sources, we show experimentally that the proposed control system allows an equilibrium state to be reached.

The paper is organized as follows. Section 2 introduces the statistical multiplexing problem and defines some notations. Section 3 presents the way we propose to solve the statistical multiplexing in a distributed manner. In Section 4 we study the equilibrium and the stability of the proposed solution.

2 Problem statement

We consider a typical broadcast system in which N video programs have to be encoded and transmitted in parallel. The compressed bitstreams are multiplexed and transmitted over a communication channel allowing a constant transmission rate R^c as represented in Figure 1. We assume that all video contents are provided with the same frame period Δt. At time index j, the j-th encoded frames are fed by all video coders. For each video stream $i \in \{1, \ldots, N\}$ an individual Rate-Distortion (R-D) control process is performed per frame generating an encoding rate R_{ij} and a distortion D_{ij} for each flow $i \in \{1, \ldots, N\}$ at time j. Each controlled frame is then stored in its corresponding buffer of the MANE, see Figure 1. The available transmission rate R^c is distributed among the N programs, $(\alpha_1 R^c, \ldots, \alpha_N R^c)$, in such a way that a fair video quality is maintained.

3 Proposed solution

In this section, we propose a distributed solution for multi video programs transmission over a shared and fixed channel rate. The idea is to regulate the video flow in two steps. The first regulation is the R-D control done for each program individually without sharing the encoding information of the other programs. The second regulation is the centralized buffer regulation during which the video quality of each stored flow in the buffers, considered located in a MANE, are analyzed and compared in order to adjust the amount of data to extract from the buffers such that comparable video quality is maintained in the N buffers. The two regulations processes are performed in a closed loop since the rate regulation feds back to each video server the level of its associated buffer to help the R-D controllers adapt their R-D trade-off so that the buffer within the MANE reaches some reference level. These two regulations processes are detailed in the following.

3.1 Rate allocation: Quality fairness

The available transmission rate R^c is allocated among video programs in a centralized way within the MANE to meet the fairness constraint. For that purpose, we assume that each video server i provides to the MANE the distortion of the j-th frame D_{ij} and the corresponding Peak Signal-to-Noise Ratio (PSNR) P_{ij} is

$$P_{ij} \quad = \quad 10log_{10}(\frac{255^2}{D_{ij}}). \tag{1}$$

The average PSNR $\bar{P}_j$ among the N program is then computed. We adopt a control-theoretic approach to regulate the video quality and model the system as a feedback control system. Using a a proportional controller (P), the rate $\alpha_{ijj} R^c$ allocated to the j-th frame in the i-th program between time j and time $j+1$ is evaluated as

$$\begin{cases} \alpha_{ij} = \frac{1}{N} + K_\alpha^P.(\bar{P}_j - P_{ij}), \\ 0 \leqslant \alpha_{ij} \leqslant 1, \; i = 1 \ldots N \end{cases} \tag{2}$$

where K_α^P is a proportional correction gain. More (less) rate is allocated to programs with a PSNR smaller (larger) than $\bar{P}_j$. With this allocation, the evolution of the level of the buffer of the i-th program between time j and time $j+1$ is

$$B_{ij+1} = B_{ij} + (R_{ij} - \alpha_{ij} R^c)\,\Delta t. \tag{3}$$

As a consequence, the level of the buffer of programs which produce encoded video with smaller PSNR than the average PSNR $\bar{P}_j$ decreases faster than programs producing video with a larger PSNR. For those programs, the buffer level may even decrease.

3.2 R-D control

For each video coder an individual R-D control process is assumed to be performed at a frame level. This control may be done, for example, by adjusting the encoding parameters with H264-AVC encoders or the number of SNR layer to transmit with H264-SVC encoders. A reference coding rate $R^0 = R^c/N$ is provided to each server. The rate R_{ij} at which the j-th frame is adjusted depending on the discrepancy between the buffer level of the i-th program and some reference buffer level B_0 as follows

$$R_{ij} = R^0 - K_R^P \left(\frac{B_{ij-1} - B^0}{\Delta T} \right), \tag{4}$$

where K_R^P is a proportional correction factor. PI controllers are widely used in feedback systems, which the integral term is proportional to both the magnitude of the error and the duration of the error. The advantage of

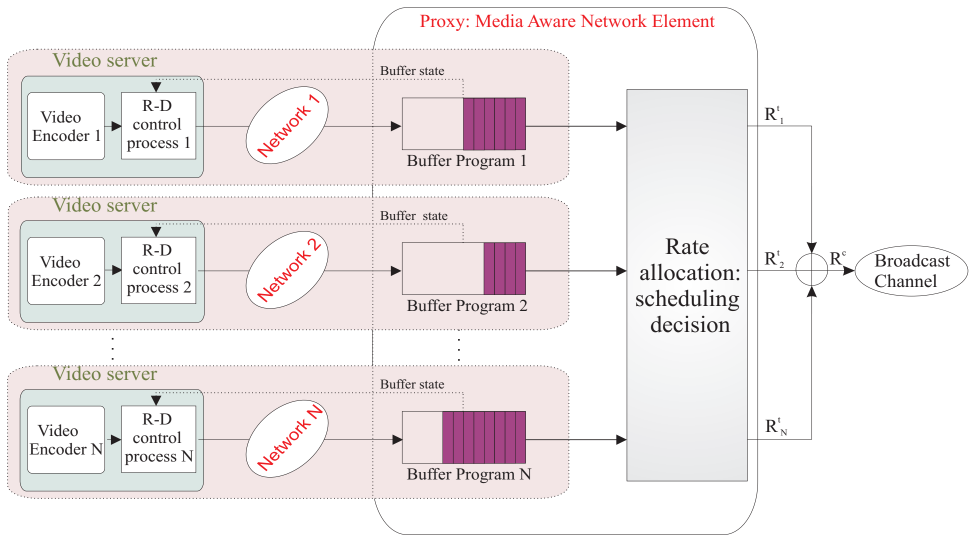

FIG. 1: Statistical multiplexing system of video streams provided by remote servers

PI controller is that its integral part may drive the steady-state error to zero, which enhances the steady-state performance of the system. This is a perfect match for the objective of regulating the encoding rate to reach stabilized buffer fullness for the N buffers in the MANE. Using a PI controller, the allocated rates fir the j-th frame and considered between time $j-1$ and time j are

$$R_{ij} = R^0 - K_R^P\left(\frac{B_{ij-1} - B^0}{\Delta T}\right) - K_R^I \sum_{k=1}^{j}\left(\frac{B_{ik-1} - B^0}{\Delta T}\right), \quad (5)$$

where K_R^I is a Integral correction factor. One sees from (4) and (5) that the encoding rate increases when the buffer is below the reference level. This control technique only requires the MANE to feed back the buffer level B_{ij-1} to each remote video encoder.

4 Analysis and results

In this section, we consider Gaussian sources clipped to $[0, 255]$, with mean 128, and variance σ_{ij}^2 with $i = \{1, \ldots, N\}$ that may vary with time. From time to time, there is a jump in the variance, small variations are modeled by uniformly distributed additional variances z_{ij} distributed in the interval $[-1, 1]$, so that

$$\sigma_{ij}^{z\,2} = \sigma_{ij}^2 + z_{ij}. \quad (6)$$

Temporal variations of the source variance correspond to scene changes in the video sequences. The R-D function of each source is

$$D_{ij}(R_{ij}) = \sigma_{ij}^{z\,2} 2^{-2R_{ij}} \quad (7)$$

with $i = 1, \ldots, N$. Combining (7) and (1), the PSNR can be expressed as a the following linear function of the rate

$$\begin{aligned} P_{ij} &= 10\log_{10}\left(\frac{255^2}{\sigma_{ij}^{z\,2}}\right) + 6R_{ij} \quad (8) \\ &= \beta_{ij} + \gamma R_{ij}. \end{aligned}$$

with $\beta_{ij} = 10\log_{10}\left(\frac{255^2}{\sigma_{ij}^{z\,2}}\right)$ and $\gamma = 6$.

4.1 Equilibrium

To study the equilibrium of the proposed system, we assume that the level of the buffers B_{ij} is constant with time. Thus, using a P controller and combining (2), (3), and (9), one gets the following system of equations

$$\begin{aligned} R_{ij} &= \left[\frac{1}{N} + K_\alpha^P\left(\frac{1}{N}\sum_{k=1}^{N} S_{kj} - S_{ij}\right)\right] R^c \quad (9) \\ &= \left[\frac{1}{N} + K_\alpha^P\left(\frac{1}{N}\sum_{k=1}^{N}\beta_{kj} - \beta_{ij} + \gamma\frac{1}{N}\sum_{k=1}^{N} R_{kj} - \gamma R_{ij}\right)\right] R^c \end{aligned}$$

corresponding to the rates at equilibrium.

4.2 Experiments

The performance of the proposed statistical multiplexing system is evaluated with three Gaussian sources each one is characterized by a time-varying variance. The transmission rate allocation is performed according to (2) using a P controller with $K_\alpha^P = 0.07$. The encoding rates are obtained from (4) when using P controller with $K_R^P = 0.05$ and from (5) when using PI controller with $K_R^P = 0.05$ and $K_R^I = 0.006$. The instantaneous variance σ^2 of the source, the buffer fullness, the PSNR, the rate allocation α, and the encoding rate of each program are represented in Figure 2. These curves have been obtained with $B^0 = 30$ bits, $R^c = 10$ bits/s and $\Delta t = 1$ s.

From Figure 2, one can see that the control system reaches equilibrium after short transient modes to satisfy the quality fairness constraint. At equilibrium, thanks to the rate allocation control in (2) based on the quality fairness constraint, almost equal PSNR are obtained for all programs. Using a P controller in the feedback control system of the R-D control, a significant discrepancy between the level of the buffers at equilibrium and the refer-

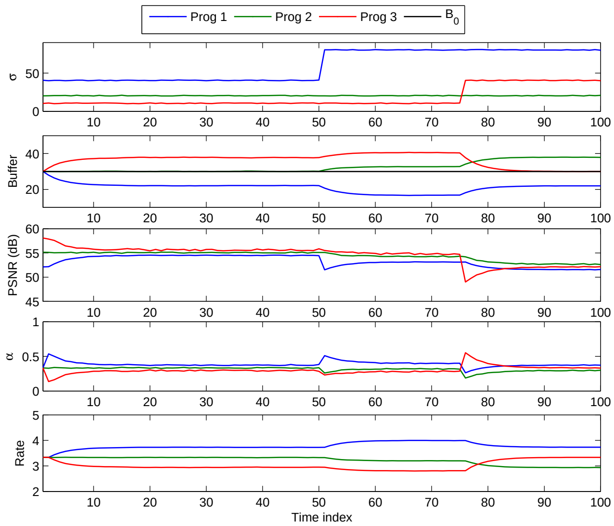

FIG. 2: Study of the equilibrium of the proposed system using a P controller

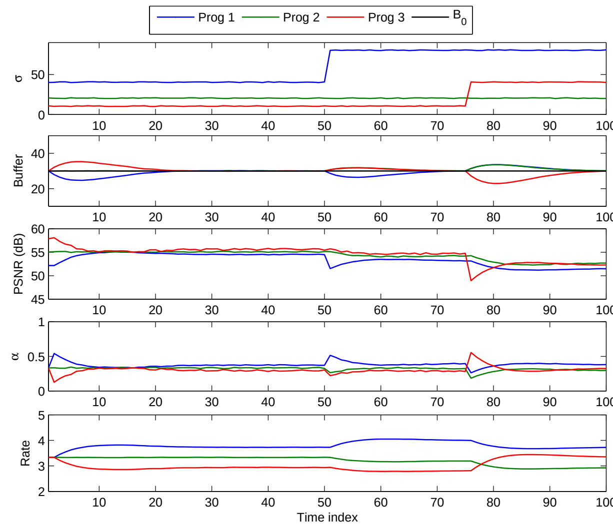

FIG. 3: Study of the equilibrium of the proposed system using a PI controller

ence buffer level is not reached. This discrepancy are fully compensated as shown in Figure 3 by using a PI control as in (5) instead of a P control in (4).

5 Conclusion

In this paper, we propose a control system that allow the statistical multiplexing of multiple video sources in a distributed way. A MANE is in charge of buffering the encoded streams and building a centralized bandwidth allocation among programs. This first regulation system should determine the appropriate amount of data to extract from each buffer based on quality information provided by each video coder in order to try to satisfy the fairness constraint. The buffer fullness is then fed back to the R-D control system of each video server to adapt the encoding rates and the video quality so that a reference buffer level is achieved. This regulation process involves a P controller for the rate allocation process and a P or PI controller for the R-D control process. Experimental tests using Gaussian signals show that the targeted quality fairness constraint is achieved. In addition, thanks to the PI controller, results show that the proposed control system allows an equilibrium state of the buffer fullness to be reached. This control system has now to be adapted to perform the control of actual video coders. The main difficulty comes from the fact that not all R-D points may be reached in a continuous way (this would require very fine grain scalability). The R-D point closest to the requested one will then have to be applied.

References

[1] Q. Chengsheng, C. Guobin, and L. Jilin, "An efficient two-pass VBR encoding algorithm for H.264," in *Int. Conference on Communications Circuits and Systems Proc.*, vol. 1, June 2006, pp. 118–122.

[2] M. Tagliasacchi, G. Valenzise, and S. Tubaro, "Minimum variance optimal rate allocation for multiplexed H.264/AVC bitstreams,," *IEEE trans on Image Processing*, vol. 17, no. 7, pp. 1129–1143, July 2008.

[3] N. Changuel, B. Sayadi, and M. Kieffer, "Predictive control for efficient statistical multiplexing of digital video programs," in *IEEE Packet Video Workshop*, May 2009, pp. 1–9.

[4] M. Rezaei, I. Bouazizi, and M. Gabbouj, "Implementing statistical multiplexing in DVB-H," *International Journal of Digital Multimedia Broadcasting*, p. 15, 2009, article ID 261231.

[5] N. Changuel, B. Sayadi, and M. Kieffer, "Joint encoder and buffer control for statistical multiplexing of multimedia contents," in *IEEE Global communications Conference: Globecom*, 2010.

[6] M. Jacobs, J. Barbarien, S. Tondeur, R. Van de Walle, T. Paridaens, and P. Schelkens, "Statistical multiplexing using svc," in *IEEE International Symposium on Broadband Multimedia Systems and Broadcasting*, 31 2008-April 2 2008, pp. 1–6.

[7] N. Changuel, N. Mastronarde, M. Van der Schaar, B. Sayadi, and M. Kieffer, "End-to-end stochastic scheduling of scalable video overtime-varying channels," in *Proceedings of the international conference on Multimedia*, ser. MM '10, 2010, pp. 731–734.

[8] Y. Huang, S. Mao, and S. Midkiff, "A control-theoretic approach to rate control for streaming videos," *IEEE Transactions on Multimedia*, vol. 11, no. 6, pp. 1072 –1081, oct. 2009.

[9] Y. Huang and S. Mao, "Analysis and design of a proportional-integral rate controller for streaming videos," in *IEEE conference on Global telecommunications*, 2009, pp. 5530–5535.