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A BROADCASTING PROTOCOL FOR COMPRESSED VIDEO

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ABSTRACT

Video broadcasting protocols can improve the efficiency of video on demand services by reducing the bandwidth required to distribute the videos that are simultaneously watched by many viewers While many broadcasting protocols have been proposed, none of them takes into account the fact that the server will broadcast compressed videos whose bandwidth requirements depend on the rate of change of the displayed images.

We present here a new broadcasting protocol specifically tailored for the task of broadcasting compressed video. Our protocol continuously broadcasts the first segment of each video in real time. It then broadcasts the remaining segments of the video at frequencies ensuring that each segment can be completely downloaded by the time the customer has finished watching the previous segment. Hence these segments do not require excess bandwidth.

1. INTRODUCTION

Despite all the attractiveness of the concept, video on demand (Wong 1988) has yet to succeed on the marketplace. One of the explanations for this lack of success is the fact that video on demand has to compete with cheaper, well-established rivals such as video rental and pay-per-view.

Video broadcasting is one of the several approaches that have been proposed for reducing the cost of video on demand. It is not a panacea since it only applies to videos that are likely to be watched at the same time by many viewers. Rather than waiting for individual requests, video broadcasting continuously transmits these videos over several data streams in such a way that no customer will have to wait more than a few minutes before being able to start viewing the video. The potential savings are quite impressive as it has been estimated that at least 40 percent of the viewers will be ordering the same 10 to 20 popular videos (Dan et al. 1994; Dan et al. 1996).

All the video broadcasting protocols that have been developed so far assume that the videos will have a fixed bandwidth corresponding to a fixed video consumption rate. This assumption is not correct because the server will broadcast compressed videos whose bandwidth requirements depend on the rate at which the images being displayed change (Garrett and Willinger 1994; Beran et al. 95). For instance, daytime action scenes and cartoons will require more bandwidth than slower moving scenes and night scenes. To ensure jitter-free delivery of video in a system allocating a fixed bandwidth to each video, we would thus have to set the video broadcasting bandwidth to the maximum bit rate required by the fastest moments of the fastest paced scenes of the video. As a result, a significant fraction of the bandwidth could remain unused most of the time.

We propose a new video broadcasting protocol that avoids this drawback. Our Variable Bandwidth Harmonic Broadcasting protocol (VBHB) divides each video to be broadcast into fixed size segments. Only the first segment of each video is broadcast in real time; the other segments are rebroadcast at a sufficient frequency to ensure that they can be completely downloaded by the set-top box by the time the customer has finished watching the previous segment of the video. Hence these segments do not require

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excess bandwidth. As a result, excess bandwidth only occurs in the first segment of each video.

The remainder of the paper is organized as follows. Section 2 reviews relevant broadcasting protocols. Section 3 discusses variable bandwidth broadcasting protocols and introduces our VBHB protocol while Section 4 compares the bandwidth requirements of the VBHB protocol with those of other broadcasting protocols. Finally Section 5 contains our conclusions.

2. VIDEO BROADCASTING PROTOCOLS

The simplest broadcasting protocol is *staggered broadcasting* (Dan et al. 1994, Almeroth and Ammar 96). Staggered broadcasting continuously retransmits each video over *k* distinct streams at equal time intervals. The only drawback of the approach is the fairly large number of data streams it requires to guarantee a reasonable waiting time. Consider, for instance, a video lasting two hours, which happens to be fairly close to the average duration of a feature movie. Guaranteeing a maximum waiting time of ten minutes would require starting a new broadcast of the video every ten minutes and a total of twelve streams.

Much more efficient protocols have been proposed, among which are Viswanathan and Imielinski's *pyramid broadcasting protocol* (Viswanathan and Imielinski 96), Aggarwal, Wolf and Yu's *permutation-based pyramid broadcasting protocol* (Aggarwal et al. 1996), Hua and Sheu's *skyscraper broadcasting protocol* (Hua and Sheu 1997), Juhn and Tseng's *harmonic broadcasting protocol* (Juhn and Tseng 1997) and its variants (Pâris et al. 1998a; Pâris et al. 1998b). All these protocols divide each video into *segments* that are simultaneously broadcast on different data streams. One of these streams transmits nothing but the first segment of the video. The other streams transmit the remaining segments at lower bandwidths. When customers want to watch a video, they first wait for the beginning of the first segment on the first stream. While they start watching that segment, their set-top box (STB) also starts downloading data from the other streams. Each individual broadcasting protocol organizes these data in a different fashion but all guarantee that the STB will be able to play each segment of the video in turn. The only drawback of the approach is the fact that the set-top box must have enough local storage to store up to 40 percent of the video. In the current state of storage technology, this implies that the STB must have a local disk.

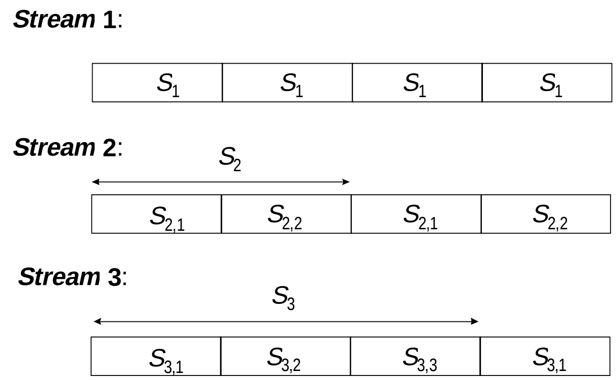

Figure 1: The first three streams of a video under harmonic broadcasting.

The most promising broadcasting protocols are the protocols based on the harmonic broadcasting protocol (Juhn and Tseng 1997; Pâris et al. 1998a) because no other protocol can deliver the same maximum waiting time without requiring much more bandwidth. *Harmonic broadcasting* (HB) divides each video into *n* segments of equal duration $d = D / n$ where *D* is the total duration of the video. It repeatedly broadcasts each segment S_i, for $1 \le i \le n$, on a separate data stream with a bandwidth b / i, where *b* is the consumption rate of the video expressed, say, in bits/s (see Figure 1).

When a customer requests a video, it waits for the start of an instance of the first segment and then starts downloading data from every stream of the video. That means that the client and the server must be able to support a bandwidth of

$$B_{HB}(n) = \sum_{i=1}^{n} \frac{b}{i} = bH(n)$$

where $H(n)$ is the n^{th} harmonic number.

Since the first segment is broadcast at a bandwidth equal to the video consumption rate *b*, the maximum amount of time customers will have to wait before viewing a video is given by the duration $d = D / n$ of that first segment.

Unfortunately HB cannot always deliver all data on time. To understand that, let us define first a *subsegment* as the fraction of a segment the client receives during *d* time units. The first segment only has one subsegment, the segment itself and every other segment S_i has *i* equal subsegments, $S_{i1},\ldots,S_{ii}$. Consider then the first two streams in

Figure 1. If the client makes its request in time to receive the second instance of S_1 and starts receiving data at time t_0, it will need *all of the data* for S_{21} by time $t_0 + 3/2d$. However, it will not receive all of that data until time $t_0 + 2d$. As it turns out, HB will not work unless the client always waits d extra time units before consuming the data.

Several variants on HB do not impose this extra waiting time. *Cautious Harmonic Broadcasting* (CHB) uses $n-1$ streams and broadcasts the first segment of the video on its first stream in a similar fashion as HB. Its second stream alternates between broadcasting S_2 and S_3 at bandwidth *b*. Then the remaining $n-3$ streams broadcast segments S_4 to S_n in a manner such that the *i*-th stream transmits segment S_{i+1} at a bandwidth $b/(i-1)$. As before, the client will start downloading data from all streams when it starts segment S_1. Hence the total bandwidth required by the CHB protocol will be given by

$$B_{CHB}(n) = 2b + \sum_{i=3}^{n-1} \frac{b}{i-1} = \frac{b}{2} + H(n-1).$$

that is, roughly *b*/2 more than the original HB protocol.

Another harmonic protocol, *Polyharmonic Broadcasting* (PHB) (Pâris et al. 1998b), imposes the same fixed delay to all customers wanting to watch a given video. Since this delay is the same for all customers, the protocol can take advantage of it to reduce the transmissions of all segments, including the first one. As a result, PHB requires more data streams but less total bandwidth than CHB to achieve the same maximum waiting time.

3. VARIABLE BANDWIDTH PROTOCOLS

We will consider videos of duration *D* and characterize each video by its average consumption rate *b* in, say, bits per second and by the minimum transmission rate b_m that can guarantee in-time delivery of all frames, always expressed in the same units as *b*. Note that b_m will not be necessary equal to the effective bandwidth of the fastest paced moments of the video $b_{\max}$ because the STB could have received ahead some data from the fastest paced scenes. This will typically happen if the previous scenes of the video required an effective bandwidth inferior to the actual transmission rate. Hence, we will always have $b \le b_m \le b_{\max}$.

The ratio $\beta = b_m / b$ will be always greater than or equal to one. It represents the bandwidth overhead resulting from the variations in the effective consumption rate. We will call it the *bandwidth overhead coefficient* (BOC) of the video.

Broadcasting protocols that require the STB to download large parts of the video while these parts are viewed by the customer are poorly suited to compressed video because these parts will have to be transmitted at a higher bandwidth to ensure jitter-free delivery of the video. Conversely, protocols that download most parts of the video ahead of time will perform better because they do not have to guarantee on-time delivery of each individual frame. The CHB protocol satisfies these requirements because the first two segments of the video are the only ones that can s be watched while they are transmitted. We will first see how it can be tailored to accommodate compressed videos and later derive from it an even better broadcasting protocol.

To evaluate CHB bandwidth requirements for compressed video, we need to characterize each segment of the video by its average consumption rate b_i and the minimum transmission rate b_{im} that can guarantee flicker-free delivery of all frames. We will always have $b_{im} > b_i$. We can now specify the bandwidths of all data streams in the following fashion:

a) stream 1 will transmit segment S_1 at bandwidth b_{1m} that is the lowest bandwidth guaranteeing on time delivery of all frames of that segment;

b) stream 2 will alternate between transmitting segments S_2 and S_3 at bandwidth equal to $\max(b_{2m}, b_3)$ that is the maximum of the lowest bandwidth guaranteeing on time delivery of all frames of segment S_2 and the average consumption rate of segment S_3 (we do not have to worry about delivering on-time the frames of S_3 since the client machine can always download it ahead of time);

c) all other segments of the video will be transmitted by streams 3 to *n*-1 and stream *i* with $3 \le i \le n-1$ will transmit segment S_{i+1} at bandwidth $\frac{b_i}{i}$.

The total bandwidth required by the CHB protocol will then be given by

$$B_{CHB}(n) = b_{1m} + \max(b_{2m}, b_3) + \sum_{i=3}^{n-1} \frac{b_i}{i}$$

The *Variable Bandwidth Harmonic Broadcasting* protocol (VBHB) we propose here improves in two ways upon the CHB protocol. First, the VBHB protocol broadcasts segments S_2 and S_3 on separate data streams at sufficient bandwidths to guarantee that these two segments will be always downloaded ahead of time. Second, it uses all the bandwidth available in the first stream to increase the size of S_1 and reduce that of S_2.

Observe that the first segment of the video needs to be broadcast every d time units to maintain a maximum waiting time equal to d time units. It needs also to be broadcast at a minimum bandwidth b_{1m} to guarantee on time delivery of all frames. The excess bandwidth $b_{1m} - b_1$ can then be used to transmit $(b_{1m} - b_1)d$ extra data, which would increase the duration of segment S_1 by

$$\frac{(b_{1m} - b_1)d}{b'}$$

time units where b' is the average consumption rate of the video during that interval. As a result, stream 2 will have to transmit a smaller segment S_2 whose duration will be now equal to

$$d - \frac{(b_{1m} - b_1)d}{b'}.$$

To ensure that the whole segment is always downloaded ahead of time, it needs to be rebroadcast every

$$d + \frac{(b_{1m} - b_1)d}{b'}$$

time units. The necessary bandwidth is then given by

$$b_{2,eff} = b_2 \frac{d - \frac{(b_{1m} - b_1)d}{b'}}{d + \frac{(b_{1m} - b_1)d}{b'}} = b_2 \frac{b' - (b_{1m} - b_1)}{b' + (b_{1m} - b_1)}.$$

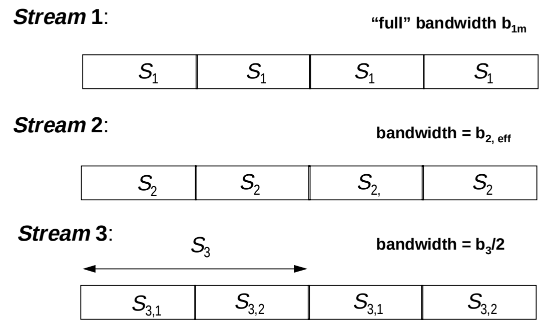

Figure 2: The first three streams of a video under VBHB.

Let us illustrate this computation in an example. Assume a bandwidth overhead coefficient $\beta = 1.5$, equal average bandwidths b_1 and b_2 for the first two segments and a maximum waiting time $d = 10$ minutes. We would then have $b_{1m} = 1.5 b_1$, which means that we would be able to transmit 15 minutes of data on the first stream each 10 minutes. Since we want segment S_3 to start with a 20 minute delay, segment S_2 will only contain five minutes of data. These data will need to be transmitted while S_1 is being watched, that is, over an interval of 15 minutes. The bandwidth required to transmit these data would be one third of the average bandwidth b_2 of segment S_2.

Given a video of duration D partitioned into n segments of average duration $d=D/n$, our protocol will allocate its n channels as follows:

a) stream 1 will transmit a segment S_1 of total duration $d + \frac{(b_{1m} - b_1)d}{b'}$ at bandwidth b_{1m};

b) stream 2 will transmit segment S_2 of duration $d - \frac{(b_{1m} - b_1)d}{b'}$ at bandwidth $b_{2,eff}$;

c) all other segments of the video will be of equal duration d and be transmitted by streams 3 to n so that stream i with $3 \le i \le n$ will transmit segment S_i at bandwidth $\frac{b_i}{i-1}$.

The total bandwidth required by our VBHB protocol will then be given by

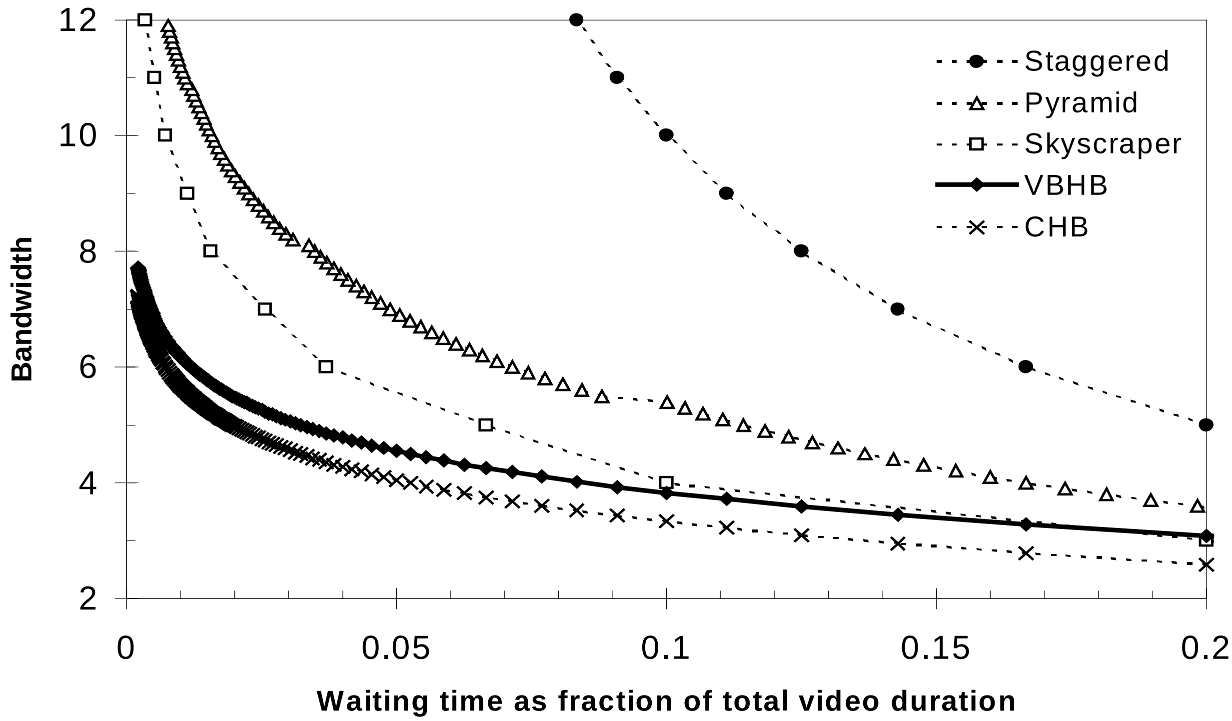

Figure 3: Bandwidth requirements of the VBHB protocol for β=1 compared to these of other broadcasting protocols.

$$B_{VBHB}(n) = b_{1m} + b_{2,eff} + \sum_{i=3}^{n} \frac{b_i}{i-1} .$$

4. COMPARISON WITH OTHER PROTOCOLS

To compare the bandwidth requirements of CHB and VBHB, we observe that the expressions for $B_{CHB}(n)$ and $B_{VBHB}(n)$ differ in the bandwidth they require to transmit segments S_2 and S_3 only. We can thus compare the two protocols without having to take into account either the number of segments of the video or the bandwidth requirements of segments S_4 to S_n

$$B_{CHB}(n) - B_{VBHB}(n) = \max(b_{2m}, b_3) - (b_{2,eff} + \frac{b_3}{2})$$

To simplify this expression, we will assume that segments S_2 and S_3 have the same average consumption rate b and an equal bandwidth overhead coefficient β. Then the effective bandwidth of channel 2 simplifies into

$$b_{2,eff} = b\frac{b-(\beta b - b)}{b+(\beta b - b)} = b\frac{2-\beta}{\beta}$$

and we have

$$B_{CHB}(n) - B_{VBHB}(n) = \beta b - b(\frac{2-\beta}{\beta} + \frac{1}{2}) = b\frac{2\beta^2+\beta-4}{2\beta} ,$$

which means that our new protocol will require less bandwidth than the CHB protocol to provide the same maximum waiting time d whenever $\beta \geq 1.19$, which is very likely to be the case in practice. The worst case for our protocol is clearly $\beta = 1$, which corresponds to a fixed bandwidth video signal. We would then have

$$B_{VBHB}(n) - B_{CHB}(n) = \frac{b}{2}$$

and our protocol would require $b/2$ units of bandwidth more than the CHB protocol.

Figure 3 shows the bandwidth versus client waiting times for staggered broadcasting, Skyscraper Broadcasting with a maximum width of 52, Pyramid Broadcasting, Cautious Harmonic Broadcasting and our VBHB protocol with β=1. To eliminate the factor D representing the duration of the video, the maximum waiting times on the x-axis are expressed as percentages of the video lengths. Even under these worst case conditions, the VBHB protocol outperforms Skyscraper Broadcasting and Pyramid Broadcasting protocols when the waiting time does not exceed 20 percent of the total duration of the video, that is a waiting time of less than 24 minutes for a two-hour video. As we have seen it earlier, VBHB outperforms CHB for all values of $\beta \geq 1.19$.

Another aspect of the performance of a broadcasting protocol is the amount of disk space it requires in the client STB. Since our new protocol only differs from the CHB protocol in the way they broadcast segments S_2 and S_3, the two protocols will have identical requirements for all values of n greater than, say, 5 or 6. To evaluate these requirements, we can follow the same approach as Juhn and Tseng in their analysis of the HB protocol (Juhn and Tseng 1997).

Let R_i be the amount of data the client STB receives while it is playing segment S_i. It is given by

$$R_i = \sum_{k=i+1}^{n} b_k$$

for $3 < i \leq n$. The average amount of data consumed while the STB is playing segment S_i is given by

$$C_i = b_i$$

and we can define B_i as the amount of data the client has in its buffer after it has finished playing segment S_i, and calculate it as

$$B_i = B_{i-1} + R_i - C_i$$

for $3 < i \leq n$ with

$$B_3 = \sum_{k=4}^{n} \frac{3}{k-1}$$

and, more generally,

$$B_i = \sum_{k=i+1}^{n} \frac{i}{k-1}$$

for $3 < i \leq n$. The maximum value of B_i will give a good approximation of the storage requirements of the two protocols. This maximum value decreases slowly with n and never exceeds 45 percent of the video for all values of $n > 10$. This is not significantly different of the storage requirements of other harmonic protocols (Juhn and Tseng 97, Pâris et al. 1998b).

5. CONCLUSIONS

Video broadcasting protocols aim at reducing the cost of video on demand services by distributing more efficiently the videos that are in high demand and are thus likely to be viewed at the same time by many viewers. Unfortunately none of the existing video broadcasting protocols takes into account the fact the server will broadcast compressed videos whose bandwidth requirements depend on the rate at which the images being displayed change. As a result, these protocols will overallocate the bandwidth required to broadcast each video. We have proposed a video broadcasting protocol that avoids this drawback. Our protocol continuously broadcasts the first segment of each video in real time. It then broadcasts the $n-1$ remaining segments of the video at frequencies ensuring that segment S_i can be completely downloaded by the time the customer has finished watching segment S_{i-1}. Hence these segments do not require excess bandwidth.

More work is still needed to evaluate the performance of the protocol using real compressed videos and to investigate other ways to map the video segments into the data streams.

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BIOGRAPHY

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