A Fast Video-on-Demand Broadcasting Scheme for Popular Videos

Jang-Ping Sheu, Han-Lih Wang, Chi-He Chang, and Yu-Chee Tseng

***Abstract*—Broadcasting is a prospective approach to support near video-on-demand services with light communication overhead. By letting clients share channels, such approaches involve partitioning a video into segments and repeatedly broadcasting these segments in multiple channels. An early paper proposed a broadcasting scheme called RFS (*recursive frequency splitting*), which can significantly reduce clients' waiting time. While efficient, RFS suffers from a high computational complexity of $O(n \log n)$, where n is the number of segments of the video, which is typically very large. This paper proposes an efficient segmentation scheme, which can significantly reduce the computational overhead by slightly sacrificing the number of segments that can be arranged as compared to RFS.**

***Index Terms*—Broadcasting, broadband networks, cable TV, video-on-demand.**

I. Introduction

ADVANCES in broadband networking and multimedia technologies offer easy, daily access to multimedia services through high-speed communication networks. One example is the Video-on-demand (VoD) service, which allows customers to connect to an on-line video server and watch videos asynchronously. A VoD system is typically implemented by a client-server architecture. However, so far VoD has not been commercially successful. One of the reasons is that it may require a number of channels (and thus communication bandwidth) proportional to the number of requests, which is infeasible when the demand is high. For example, a video in MPEG-2 compressed format requires a bandwidth of 0.5 MB/sec [17]. Times the number of requests, extremely high disk I/O and communication bandwidth are needed.

To reduce the cost, many broadcast-based approaches are proposed to provide near-VoD services. The *batching* approach collects a group of requests that arrive close in time, and serves them altogether when a channel is available [1], [3], [4]. Two *patching* schemes [5], [7] are proposed on top of the batching approach to allow late-coming clients to join the service. Adaptive batching schemes are proposed in [12], [13]. One prospective direction is to partition a video into multiple segments and broadcast them cooperatively by multiple channels [2], [6], [8]–[11], [14]–[16]. Since the server's broadcasting activity is independent of the arrivals of requests, such solutions are more appropriate for popular or hot videos that may attract many viewers at a certain period of time. The *pyramid scheme* [2], [16] can reduce clients' maximum waiting time in an exponential ratio with respect to the number of channels used. The *Fast Broadcasting (FB) scheme* [8], [9] only incurs $D/(2^k - 1)$ waiting time when using k channels, where D is the length of the video. The *PAGODA scheme* [10], [11] can further reduce the waiting time to $D/(4(5^{(k/2)-1}) - 1)$ if k is even, and $D/(2(5^{\lfloor (k/2) \rfloor}) - 1)$ if k is odd. In [6], Hu gives a comprehensive study of existing broadcasting protocols, and proposes a generalized analytical approach to evaluate such protocols. The recently proposed *Recursive Frequency Splitting (RFS) scheme* [14] can further reduce the waiting time significantly.

While efficient, the RFS scheme [14] suffers from a high computational complexity of $O(n \log n)$, where n is the number of segments that the video is partitioned into. Since n is typically very large, reducing the overhead is desirable. In this paper, we propose an efficient segmentation scheme, which can significantly reduce the computational overhead by slightly sacrificing the number of segments (i.e., n) that can be arranged.

The rest of this paper is organized as follows. Our new scheme is proposed in Section II. A further refinement is presented in Section III. Performance comparison is in Section IV.

II. The Proposed Broadcasting Scheme

Consider a video V of length D. We are given k channels, $C_0, C_1, \ldots, C_{k-1}$, each of a bandwidth capable of supporting broadcasting V. The problem is to find a largest possible n such that V is partitioned into n equal-length segments $S_1, S_2, \ldots, S_n$ and to obtain a placement of these n segments on the given k channels such that any client, after waiting no longer than D/n time, can start enjoying viewing V without any disruption.

Note that at this point, the value of n is not known yet. Its value will be an output of our algorithm. Once n is known, we can partition the k channels into time slots of length $\delta = D/n$. A client has to wait no longer than one time slot to start viewing V. Therefore, the maximum waiting time is D/n. A general guideline to guarantee a nondisrupted playback is given in [14].

Lemma 1: The i-th segment $S_i, 1 \leq i \leq n$, must be broadcast with a period p such that $p \leq i$.

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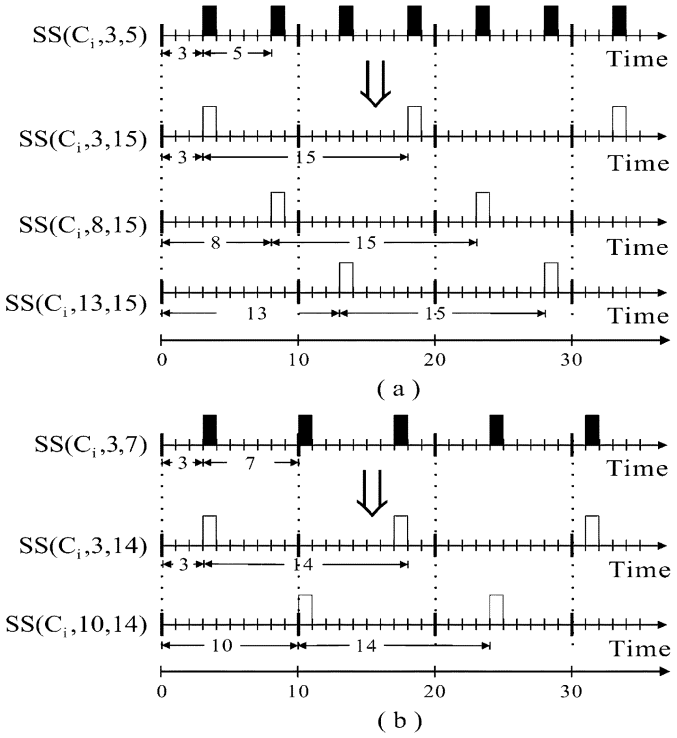

Fig. 1. (a) Splitting slot sequence $\mathrm{SS}(C_i, 3, 5)$ by a factor of 3, and (b) splitting $\mathrm{SS}(C_i, 3, 7)$ by a factor of 2.

Our goal is to assign for each segment a sequence of periodical time slots as defined below.

Definition 1: A *slot sequence* $\mathrm{SS}(C_i, \eta, p)$ is an infinite sequence of time slots $[\eta, \eta + p, \eta + 2p, \ldots]$ belonging to channel C_i, beginning at slot η, and repeating infinitely with a period of p slots, where C_i is one of the k channels, $\eta \geq 0$ is an integer (i.e., offset), and $p \geq 1$ is an integer (i.e., period), $0 \leq \eta \leq p-1$.

In this work, we will count time slots of a channel starting from 0, instead of 1. Several examples of slot sequences are shown in Fig. 1.

The most bandwidth-efficient slot assignment, according to Lemma 1, is to assign a slot sequence of period i to S_i. However, this is not always feasible since two slot sequences on the same channels with periods that are mutually prime will eventually collide with each other. For example, given any two slot sequences $\mathrm{SS}(C_i, \eta, p)$ and $\mathrm{SS}(C_i, \eta', p')$ such p and p' are mutually prime, it is a simple result in number theory that we can find two integers i and j such that $\eta + ip = \eta' + jp'$. Thus, S_p and $S_{p'}$ cannot be placed in the same channel unless some bandwidth is sacrificed. When assigning a slot sequence $\mathrm{SS}(C_j, \eta, p)$ to S_i such that $p < i$, we say that the amount of waste is $(1/p) - (1/i)$. So we should make p as large as possible to reduce the waste.

Our scheme is based on a concept called "frequency-splitting" to generate slot sequences of different periods, as formulated below.

Lemma 2: A slot sequence $\mathrm{SS}(C_i, \eta, p)$ can be split by a factor of α into α slot sequences

$$\mathrm{SS}(C_i, \eta, \alpha p), \mathrm{SS}(C_i, \eta + p, \alpha p), \mathrm{SS}(C_i, \eta + 2p, \alpha p), \ldots, \mathrm{SS}(C_i, \eta + (\alpha - 1)p, \alpha p).$$

Two splitting examples are in Fig. 1. Below we further generalize the result by grouping multiple slot sequences into a set, as defined below.

Definition 2: The union of q slot sequences with the same period p, namely $\mathrm{SS}(C_i, \eta_1, p)$, $\mathrm{SS}(C_i, \eta_2, p), \ldots, \mathrm{SS}(C_i, \eta_q, p)$, can be written as a *slot sequence set* $\mathrm{SSS}(C_i, \{\eta_1, \eta_2, \ldots, \eta_q\}, p)$.

Lemma 3: A slot sequence set $\mathrm{SSS}(C_i, \{\eta_1, \eta_2, \ldots, \eta_q\}, p)$ can be split by a factor of α into a slot sequence set $\mathrm{SSS}(C_i, \{\eta_a + bp \,|\, a = 1 \ldots q, b = 0 \ldots \alpha - 1\}, \alpha p)$.

For example, the $\mathrm{SSS}(C_i, \{3, 10\}, 14)$ in Fig. 1(b) can be split by a factor of 3 into $\mathrm{SSS}(C_i, \{3, 10, 17, 24, 31, 38\}, 42)$.

The basic idea of our scheme is to represent available slots as slot sequence sets and store them in a resource pool. We will use above lemma to split slot sequences, and multiple video segments will be assigned in groups, until the resource pool is exhausted. The scheme is formally derived below. The outputs are an n and the assignment of each segment $S_i, i = 1 \ldots n$, to one slot sequence.

1) Let the resource pool, denoted by a set *POOL*, be

$$\mathrm{POOL} = \{\mathrm{SSS}(C_i, \{0, 1, 2, \ldots, p(i) - 1\}, p(i)) \,|\, i = 0 \ldots k - 1\},$$

where $p(0) = 1$ and $p(i)$ is the i-th prime number when $i \geq 1$ (e.g., $p(1) = 2, p(2) = 3$, and $p(3) = 5$). Intuitively, this represents the set of all free slot sequences at the beginning.

2) Assign $\mathrm{SS}(C_i, 0, p(i))$ to $S_{p(i)}, i = 0 \ldots k-1$, and delete these slot sequences from *POOL*.

3) Let j be the smallest index such that segment S_j is not assigned to any slot sequence yet. Let $\mathrm{SSS}(C_{i1}, \Psi_1, p_1)$ be the slot sequence set in *POOL* such that its period, p_1, is the smallest (in case that *POOL* doesn't have any slot sequence set remaining, we can simply imagine that $p_1 = \infty$). Also, let $\mathrm{SSS}(C_{i2}, \Psi_2, p_2)$ be the slot sequence set in *POOL* such that its period, p_2, is the second smallest (in case that *POOL* has only one slot sequence set remaining, we simply let $p_2 = 2p_1$). We consider the relationship between j and p_1. There are three cases:

   a) If $j < p_1$, then no slot sequence in *POOL* can accommodate segment S_j. So we terminate this algorithm.

   b) If $p_1 \leq j < 2 \cdot p_1$, then we sequentially assign the slot sequences in $\mathrm{SSS}(C_{i1}, \Psi_1, p_1)$ to segments $S_j, S_{j+1}, \ldots, S_{2p_1 - 1}$ until either all segments are successfully assigned or the slot sequences in $\mathrm{SSS}(C_{i1}, \Psi_1, p_1)$ have been exhausted. Then go back to the beginning of step 3.

   c) If $2 \cdot p_1 \leq j$, then we split the slot sequence set $\mathrm{SSS}(C_{i1}, \Psi_1, p_1)$ by a factor of two into, say $\mathrm{SSS}(C_{i1}, \Psi_1', 2p_1)$, by applying Lemma 3. Then we sequentially assign the slot sequences in $\mathrm{SSS}(C_{i1}, \Psi_1', 2p_1)$ to segments $S_j, S_{j+1}, \ldots, S_{2p_2 - 1}$ until either all segments are successfully assigned or the slot sequences in $\mathrm{SSS}(C_{i1}, \Psi_1', 2p_1)$ have been exhausted. Then go back to the beginning of step 3.

TABLE I
THE ASSIGNMENT EXAMPLE WHEN $k = 4$ CHANNELS.

iteration	segments assigned	*POOL* (after the assignment)
0	S_1, S_2, S_3, S_5	$SSS(C_1, \{1\}, 2), SSS(C_2, \{1, 2\}, 3), SSS(C_3, \{1, 2, 3, 4\}, 5)$
1	S_4	$SSS(C_2, \{1, 2\}, 3), SSS(C_1, \{3\}, 4), SSS(C_3, \{1, 2, 3, 4\}, 5)$
2	S_6, S_7	$SSS(C_1, \{3\}, 4), SSS(C_3, \{1, 2, 3, 4\}, 5), SSS(C_2, \{4, 5\}, 6)$
3	S_8, S_9	$SSS(C_3, \{1, 2, 3, 4\}, 5), SSS(C_2, \{4, 5\}, 6)$
4	S_{10}, S_{11}	$SSS(C_2, \{4, 5\}, 6), SSS(C_3, \{3, 4, 6, 7, 8, 9\}, 10)$
5	$S_{12}, S_{13}, S_{14}, S_{15}$	$SSS(C_3, \{3, 4, 6, 7, 8, 9\}, 10)$
6	$S_{16}, S_{17}, S_{18}, S_{19}$	$SSS(C_3, \{8, 9\}, 10)$
7	$S_{20}, S_{21}, S_{22}, S_{23}$	$\emptyset$
8	$\emptyset$	$\emptyset$

Note that step 3a is the only exit of the algorithm. Steps 3b and 3c are where we assign multiple segments in one step. According to our experience, in most cases step 3c will be executed as opposed to step 3b. The following is an example for $k = 4$ channels.

1) In the beginning, we separate channels C_0, C_1, C_2, and C_3 into slot sequence sets $\mathrm{SSS}(C_0, \{0\}, 1), \mathrm{SSS}(C_1, \{0,1\}, 2), \mathrm{SSS}(C_2, \{0,1,2\}, 3)$, and $\mathrm{SSS}(C_3, \{0, 1, 2, 3, 4\}, 5)$.
2) Then we assign $\mathrm{SS}(C_0, 0, 1)$ to $S_1, \mathrm{SS}(C_1, 0, 2)$ to $S_2, \mathrm{SS}(C_2, 0, 3)$ to S_3, and $\mathrm{SS}(C_3, 0, 5)$ to S_5.
3) In the first iteration, $j = 4, p_1 = 2$, and $p_2 = 3$. We split $\mathrm{SSS}(C_1, \{1\}, 2)$ into $\mathrm{SSS}(C_1, \{1, 3\}, 4)$ and then assign $\mathrm{SS}(C_1, 1, 4)$ to S_4.
4) In the second iteration, $j = 6, p_1 = 3$, and $p_2 = 4$. We split $\mathrm{SSS}(C_2, \{1, 2\}, 3)$ into $\mathrm{SSS}(C_2, \{1, 2, 4, 5\}, 6)$ and then assign $\mathrm{SSS}(C_2, \{1, 2\}, 4)$ to $\{S_6, S_7\}$.
5) In the third iteration, $j = 8, p_1 = 4$, and $p_2 = 5$. We split $\mathrm{SSS}(C_1, \{3\}, 4)$ into $\mathrm{SSS}(C_1, \{3, 7\}, 8)$ and then assign $\mathrm{SSS}(C_1, \{3, 7\}, 8)$ to $\{S_8, S_9\}$.
6) In the fourth iteration, $j = 10, p_1 = 5$, and $p_2 = 6$. We split $\mathrm{SSS}(C_3, \{1, 2, 3, 4\}, 5)$ into $\mathrm{SSS}(C_3, \{1, 2, 3, 4, 6, 7, 8, 9\}, 10)$ and then assign $\mathrm{SSS}(C_1, \{1, 2\}, 10)$ to $\{S_{10}, S_{11}\}$.
7) In the fifth iteration, $j = 12, p_1 = 6$, and $p_2 = 10$. We split $\mathrm{SSS}(C_2, \{4, 5\}, 6)$ into $\mathrm{SSS}(C_2, \{4, 5, 10, 11\}, 12)$ and then assign $\mathrm{SSS}(C_2, \{4, 5, 10, 11\}, 12)$ to $\{S_{12}, S_{13}, S_{14}, S_{15}\}$. Note that in this case we have exhausted all slot sequences available in $\mathrm{SSS}(C_2, \{4, 5, 10, 11\}, 12)$.
8) In the sixth iteration, $j = 16, p_1 = 10$, and $p_2 = \infty$. In this case, we will enter step 3b and assign $\mathrm{SSS}(C_3, \{3, 4, 6, 7\}, 10)$ to $\{S_{16}, S_{17}, S_{18}, S_{19}\}$.
9) In the seventh iteration, $j = 20, p_1 = 10$, and $p_2 = 2p_1 = 20$. Again, we will enter step 3b, which will split $\mathrm{SSS}(C_3, \{8, 9\}, 10)$ into $\mathrm{SSS}(C_3, \{8, 9, 18, 19\}, 20)$ and then assign $\mathrm{SSS}(C_3, \{8, 9, 18, 19\}, 20)$ to $\{S_{20}, S_{21}, S_{22}, S_{23}\}$.
10) In the eighth iteration, since all slot sequences have been exhausted, $j = 24, p_1 = \infty$, and $p_2 = \infty$. We will enter step 3a, and the assignment will be terminated.

III. A FURTHER REFINEMENT

We make two observations on the above scheme. First, after the initial assignment in steps 1 and 2, *POOL* has slot sequences of periods $p(1), p(2), \ldots, p(k-1)$. Second, since slot sequence sets are always split by a factor of 2, the only periods that may appear in *POOL* is $2^i p(1), 2^i p(2), \ldots, 2^i p(k-1)$ for some i. For example, in Table I, the possible periods in *POOL* are 2, 3, 4, 5, 6, 8, 10, 12, 20, etc.

The basic idea in the refinement is to change the initial value of *POOL* so that there are more choices of periods in *POOL*. As noted earlier, assigning $\mathrm{SS}(C_i, \eta, p)$ to S_j causes a bandwidth waste of $(1/p) - (1/j)$. A more variety of periods may incur less waste. Given k channels, the refined scheme works as follows.

1) Still, let the resource pool, denoted by a set *POOL*, be

$$\mathrm{POOL} = \{\mathrm{SSS}(C_i, \{0, 1, 2, \ldots, p(i) - 1\}, p(i)) \,|\, i = 0 \ldots k-1\}.$$

Then, for each $\mathrm{SSS}(C_i, \{0, 1, 2, \ldots, p(i) - 1\}, p(i)), i = 2 \ldots k-1$, keep the first $\lceil (p(i)/2) \rceil$ slot sequences unchanged, and for each of the remaining $\lfloor (p(i)/2) \rfloor$ slot sequences, split it by a factor of $2j + 1$ such that $j = 1 \ldots \lfloor (p(i)/2) \rfloor$.
2) For each value of p that appears in *POOL* as a period of some slot sequence set, allocate one slot sequence from the corresponding SSS and assign it to segment S_p. Then delete the slot sequence from *POOL*.
3) Repeat steps 3 in the original scheme in Section II.

Table II illustrates the refined assignment example with 4 channels. Since the difference between the refined assignment and the original assignment only happens at the first two steps, we only discuss the first few iterations below:

1) In the beginning, we separate channels C_0, C_1, C_2, and C_3 into slot sequence sets $\mathrm{SSS}(C_0, \{0\}, 1), \mathrm{SSS}(C_1, \{0, 1\}, 2), \mathrm{SSS}(C_2, \{0, 1, 2\}, 3)$, and $\mathrm{SSS}(C_3, \{0, 1, 2, 3, 4\}, 5)$.
2) Then, we separate $\mathrm{SSS}(C_2, \{2\}, 3)$ into $\mathrm{SSS}(C_2, \{2, 5, 8\}, 9)$, separate $\mathrm{SSS}(C_3, \{3\}, 5)$ into $\mathrm{SSS}(C_3, \{3, 8, 13\}, 15)$, and separate $\mathrm{SSS}(C_3, \{4\}, 5)$ into $\mathrm{SSS}(C_3, \{4, 9, 14, 19, 24\}, 25)$.
3) Assign $\mathrm{SS}(C_0, 0, 1)$ to $S_1, \mathrm{SS}(C_1, 0, 2)$ to $S_2, \mathrm{SS}(C_2, 0, 3)$ to $S_3, \mathrm{SS}(C_3, 0, 5)$ to $S_5, \mathrm{SS}(C_2, 59)$ to $S_9, \mathrm{SS}(C_3, 3, 15)$ to S_{15}, and $\mathrm{SSS}(C_3, 4, 25)$ to S_{25}.
4) The following steps are quite similar to the original scheme. Note that in the ninth iteration, we have $j = 21, p_1 = 25$, and $p_2 = 50$. Although the slot sequences have not been exhausted yet, we have to enter step 3a and terminate the algorithm.

TABLE II
THE REFINED ASSIGNMENT EXAMPLE WHEN $k = 4$ CHANNELS.

iteration	segments assigned	$POOL$ (after the assignment)
0	$S_1, S_2, S_3, S_5, S_9, S_{15}, S_{25}$	$SSS(C_1,\{1\},2), SSS(C_2,\{1\},3), SSS(C_3,\{1,2\},5)$ $SSS(C_2,\{5,8\},9), SSS(C_3,\{8,13\},15), SSS(C_3,\{9,14,19,24\},25)$
1	S_4	$SSS(C_2,\{1\},3), SSS(C_1,\{3\},4), SSS(C_3,\{1,2\},5)$ $SSS(C_2,\{5,8\},9), SSS(C_3,\{8,13\},15), SSS(C_3,\{9,14,19,24\},25)$
2	S_6, S_7	$SSS(C_1,\{3\},4), SSS(C_3,\{1,2\},5)SSS(C_2,\{5,8\},9),$ $SSS(C_3,\{8,13\},15), SSS(C_3,\{9,14,19,24\},25)$
3	S_8	$SSS(C_3,\{1,2\},5), SSS(C_1,\{7\},8)S(C_2,\{5,8\},9),$ $SSS(C_3,\{8,13\},15), SSS(C_3,\{9,14,19,24\},25)$
4	$S_{10}, S_{11}, S_{12}, S_{13}$	$SSS(C_2,\{7\},8), SSS(C_2,\{5,8\},9), SSS(C_3,\{9\},10),$ $SSS(C_3,\{8,13\},15), SSS(C_3,\{9,14,19,24\},25)$
5	S_{14}	$SSS(C_2,\{5,8\},9), SSS(C_3,\{9\},10),$ $SSS(C_3,\{8,13\},15), SSS(C_3,\{9,14,19,24\},25)$
6	S_{16}, S_{17}	$SSS(C_3,\{9\},10), SSS(C_3,\{8,13\},15), SSS(C_3,\{9,14,19,24\},25)$
7	S_{18}	$SSS(C_3,\{8,13\},15), SSS(C_3,\{9,14,19,24\},25)$
8	S_{19}, S_{20}	$SSS(C_3,\{9,14,19,24\},25)$
9	$\emptyset$	$SSS(C_3,\{9,14,19,24\},25)$

TABLE III
THE NUMBERS OF MAXIMUM SEGMENTS (n) OFFERED BY DIFFERENT SCHEMES.

channels (k)	3	4	5	6	7	8	9	10	11	12	13	14	15
RFS [14]	9	25	73	201	565	1522	4284	11637	31677	86428	237705	653958	1792699
our refined scheme	9	20	71	193	509	1395	3535	9087	27423	73215	192639	503295	1212415
our basic scheme	9	23	63	135	319	1055	2431	6399	17919	51199	131215	290815	655359
New PAGODA [10]	9	26	66	172	442	1183	3092	8285	N/A	N/A	N/A	N/A	N/A
PAGODA [11]	9	19	49	99	249	499	1249	2499	6249	12499	31249	62499	156249
FB [8, 9]	7	15	31	63	127	255	511	1023	2047	4095	8191	16383	32767

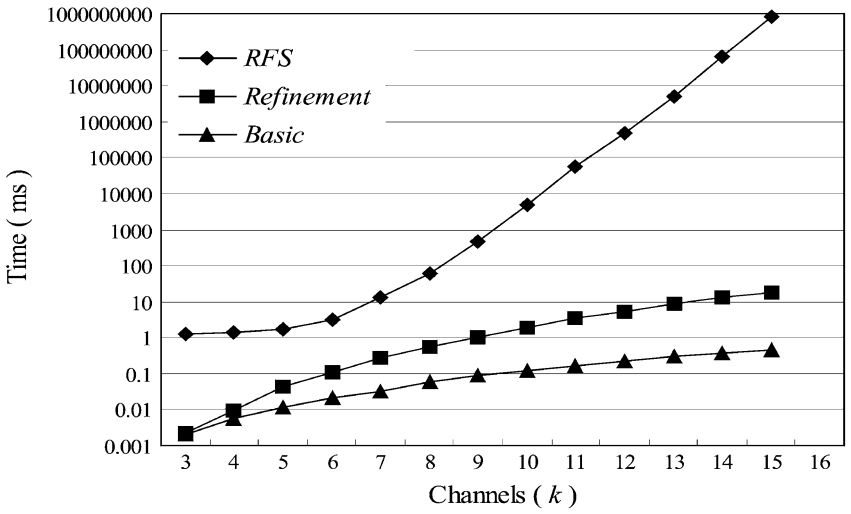

Fig. 2. Comparison of computational overhead of our and RFS schemes.

IV. PERFORMANCE ANALYSIS AND COMPARISON

Table III compares the number of segments that can be arranged (i.e., n) by different schemes. The inverse of n represents clients' waiting time. As can be seen, our schemes outperform the FB, PAGODA, and new PAGODA schemes as k enlarges, but slightly fall behind the RFS scheme. Also note that the new PAGODA scheme is built purely by heuristic and thus a general result for n is not available.

The buffer requirement at the client side is also an important issue for video broadcasting. Since the server side broadcasts k segments every time slot when using k channels, we have to buffer at most k more segments but consume only one segment from the buffer after every time slot. However, we do not need to buffer S_j at the i-th time slot such that $0 < j < i$. So, the maximum buffer requirement at the client side when using k channels must be bounded by:

$$B_k = \max_{0<i\le n} \left\{ k \times i - \sum_{j=1}^{i} \left\lfloor \frac{i}{p_{k,j}} \right\rfloor \right\},$$

where $p_{k,j}$ the time period of the slot sequence assigned to the segment S_j when using k channel.

Next, we analyze the time complexity of our schemes. In each assignment we only scan *POOL* for the smallest and second smallest periods. Also observe that the size of *POOL* is $O(k)$ for the basic scheme, and $O(k^2)$ for the refined scheme. If *POOL* is maintained by a heap tree, then both deletion and insertion operations to the heap will incur a cost of $O(\log k)$ for both schemes. So the time complexity for both the basic and refined schemes is $O(n \log k)$.

In comparison, the RFS scheme is also derived based on the concept of frequency splitting. However, segments are assigned one at a time in RFS. To assign a segment, the whole *POOL* has to be scanned to minimize the bandwidth waste. The overall computational cost is $O(n^2)$. Further, in practice our schemes assign multiple segments at a time. The actual computational overhead should be much smaller than $O(n \log k)$. Fig. 2 shows our simulation result on computational cost when running the segment assignments on a Pentium III, 450 MHz, IBM-compatible PC with 128 Mb RAM. As can be seen, the overhead of the proposed schemes are much smaller than that of RFS. Even when k is quite large, only a few milliseconds are needed.

V. Conclusion

We have proposed efficient segment-scheduling schemes to support video broadcasting. The schemes effectively arrange segments by assigning multiple segments at one time. It significantly reduces the computational overhead by slightly sacrificing clients' waiting time as compared to the RFS scheme.

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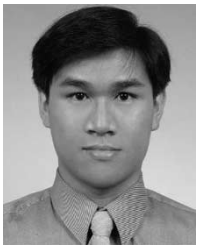

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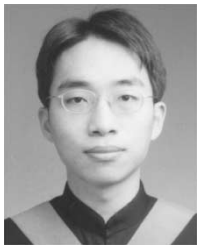

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