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Research Article

Efficient Periodic Broadcasting for Mobile Networks at Small Client Receiving Bandwidth and Buffering Space

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Periodic broadcasting is an effective approach for delivering popular videos. In general, this approach does not provide interactive (i.e., VCR) functions, and thus a client can tolerate playback latency from a video server. The concept behind the approach is partitioning a video into multiple segments, which are then broadcast across individual communication channels in terms of IP multicast. The method improves system throughput by allowing numerous clients to share the channels. For many broadcasting schemes, client receiving bandwidth must equal server broadcasting bandwidth. This limitation causes these schemes to be infeasible in mobile networks because increasing receiving bandwidth at all client sites is expensive, as well as difficult. To alleviate this problem, the fibonacci broadcasting (FiB) scheme allows a client with only two-channel bandwidth to receive video segments. In comparison with other similar schemes, FiB yields smallest waiting time. Extending FiB, this work proposes a new scheme (called FiB+) to achieve smaller client buffering space and the same waiting time under two-channel receiving bandwidth. Extensive analysis shows that FiB+ can yield 34.5% smaller client buffer size than that of FiB. Further simulation results also indicate that FiB+ requires lower client buffering space than several previous schemes.

1. Introduction

Video-on-demand (VOD) services have become popular due to advances in network and computer technology [1, 2]. A VOD system may easily run out of bandwidth since the growth in bandwidth can never keep up with the growth in the number of clients. To alleviate the problem, one way is to simply broadcast popular videos. According to the study in [3, 4], a few very popular videos constitute most client requests. Data broadcasting is thus suitable to transfer popular videos that may be interesting to many clients in a particular period of time. An efficient method for broadcasting a popular video is to divide it into segments, which are simultaneously and periodically transmitted across individual communication channels in terms of IP multicast [5]. Because video broadcasting does not provide VCR functions, a client is able to tolerate playback latency. To ensure continuous playback, clients must simultaneously download and save the video segments from these channels. The clients usually have to wait for the occurrence of the first segment before they can start playing the video. Since the clients cannot watch the video immediately, the broadcasting schemes provide near VOD services.

The fast broadcasting (FB) scheme [6] improves segment partition and arrangement to yield shorter waiting time. To achieve near-minimum waiting time, the recursive frequency-splitting (RFS) scheme [7] broadcasts each segment at the frequency that can keep continuous video playback. A scalable binomial broadcasting scheme [8] transfers a variable-length video using constant bandwidth. To simplify the implementation of multiple channels, the PAS scheme [9] broadcasts video segments over a single channel. The reverse-order scheduling (ROS) scheme [10] transmits segments of the same group in reverse order over a single channel to save buffering space.

With the fast growth of wireless networks, mobile video services become more and more popular. Broadcasting videos under rather restricted client resources is increasingly important. The following schemes address the savings on client buffer size and bandwidth. Modifying the FB scheme [6], the reverse fast broadcasting (RFB) scheme [11] buffers 25% of video size, just half of what is required by FB. By combining RFS and RFB, the hybrid broadcasting scheme (HyB) [12] achieves small client buffering space and waiting time. Different RFB-based hybrid schemes were proposed in [13, 14]. The skyscraper broadcasting (SkB) scheme [15] allows a client to download video data using only a bandwidth of two channels. The client-centric approach (CCA) [16] also permits a client downloading video data via a small number of channels, and CCA+ [17] further yields smaller waiting time than SkB. Like SkB and CCA+, the fibonacci broadcasting (FiB) scheme [18] supports a client with two-channel bandwidth but achieves the minimum waiting time. The authors in [19] proposed an FB-based scheme for heterogeneous clients. The studies in [20, 21] deploy a proxy in VoD systems to serve heterogeneous clients.

The contributions of this study are summarized as follows.

(1) Extending FiB, this work proposes a promising scheme, called FiB+, to deliver near VOD services to clients with small receiving bandwidth and buffering space. In comparison with FiB, FiB+ still yields the minimum waiting time under two-channel receiving bandwidth; moreover, FiB+ can save about 34.5% of buffer size.

(2) The paper investigates the total client buffer requirements for FiB+ and explains why this scheme requires smaller buffering space than FiB. We further derive the maximum number of segments buffered by an FiB+ client mathematically. Extensive performance analysis has been conducted on FiB+ by comparing a number of past reported counterparts. The results indicate that FiB+ yields relatively lower client buffer requirements than most schemes.

The remainder of this study is organized as follows. The FiB scheme is introduced in Section 2. Section 3 presents FiB+. This section also verifies the on-time video delivery under two-channel client bandwidth. Section 4 evaluates the performance of FiB+. Brief conclusions are drawn in Section 5.

2. Review of FiB

Let k be the number of server channels throughout the paper. The FiB scheme [18] unequally divides a video of length L into k segments, denoted by $S_1, S_2, \ldots, S_k$ in sequence. The length of a segment S_i is based on the following equation and equals $Ln_i / \sum_{p=1}^{k} n_p$ as follows:

$$n_i = \begin{cases} 1, & i = 1 \\ 2, & i = 2 \\ n_{i-1} + n_{i-2}, & 3 \le i \le k. \end{cases} \quad (1)$$

Assume that the data transmission rate of each channel equals the playback rate b. The server then periodically broadcasts segment S_i on channel C_i, as illustrated in Figure 1. In the figure, segments downloaded and played by a client are gray. When a client wants to watch a video, the client first downloads segments S_1 and S_2 on the first two channels C_1 and C_2. Once finishing receiving the segment S_1, the client continuously accepts segment S_2 and newly downloads segment S_3 on channel C_3. The client repeats the process, which starts downloading segment S_i on channel C_i once finishing receiving segment S_{i-2} from channel C_{i-2}, until all the segments are loaded. An FiB client thus requires a bandwidth of only two channels to download video segments.

Table 1: List of terms used in the proposed scheme and their respective definitions.

Term	Definition
L	Video length
k	Number of broadcasting channels for each video on the server side
C_i	ith broadcasting channel, $i = 1, \ldots, k$
N	Number of segments of a video
S_i	ith video segment, $i = 1, \ldots, N$
n_i	Number of segments transferred on channel C_i
m_i	Total segments transferred on channels C_1 through C_i, $m_i = \sum_{p=1}^{i} n_p$
b	Video playback rate assumed to equal the data transmission rate of each channel
T_0	Starting time to watch the first segment
Time unit	Basic unit on time axis, whose length equals the length of a segment (i.e., L/N)

3. FiB+

Some of the frequently used terms and their definitions are listed in Table 1. On the server side, the FiB+ scheme includes the following steps.

(1) The server equally divides a video into N segments, denoted by $S_1, S_2, \ldots, S_N$ in sequence, where $N = \sum_{p=1}^{k} n_p$, where n_p is based on (1). The length of each segment thus equals L/N. From (1), we further yields

$$m_i = \sum_{p=1}^{i} n_p = n_{i+2} - 2. \quad (2)$$

See Appendix A for details. Thus, $N = n_{k+2} - 2$. The FiB+ scheme then assembles segments $S_{n_{i+1}-1}$ to $S_{n_{i+2}-2}$ (i.e., $S_{m_{i-1}+1}$ to S_{m_i}) into group G_i sequentially, as illustrated in Figure 2(a). The number of segments of group G_i thus equals n_i. For instance, group G_4 includes segments S_7 to S_{11}, and $n_4 = 5$.

(2) Channel C_i, where $1 \le i \le k-2$, periodically broadcasts the segments of group G_i in sequence, as shown in Figure 2(b). That is, segments $S_{n_{i+1}-1}$ to $S_{n_{i+2}-2}$ are transferred one by one on channel C_i.

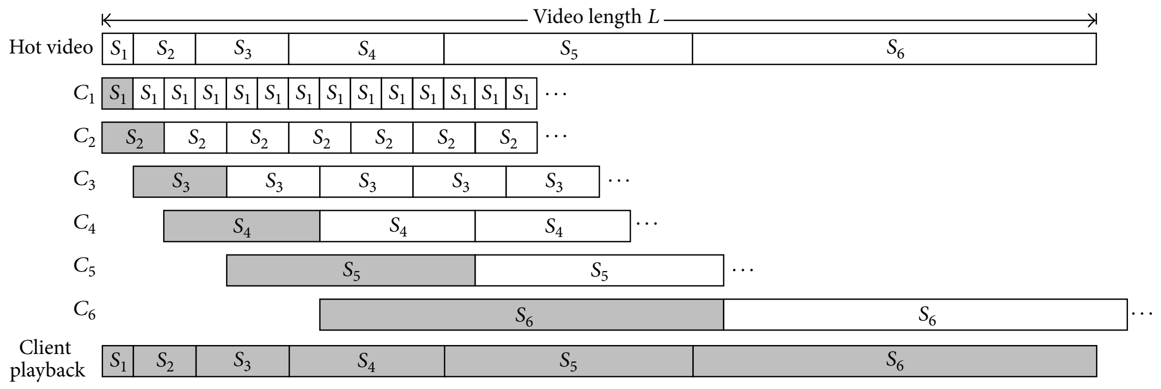
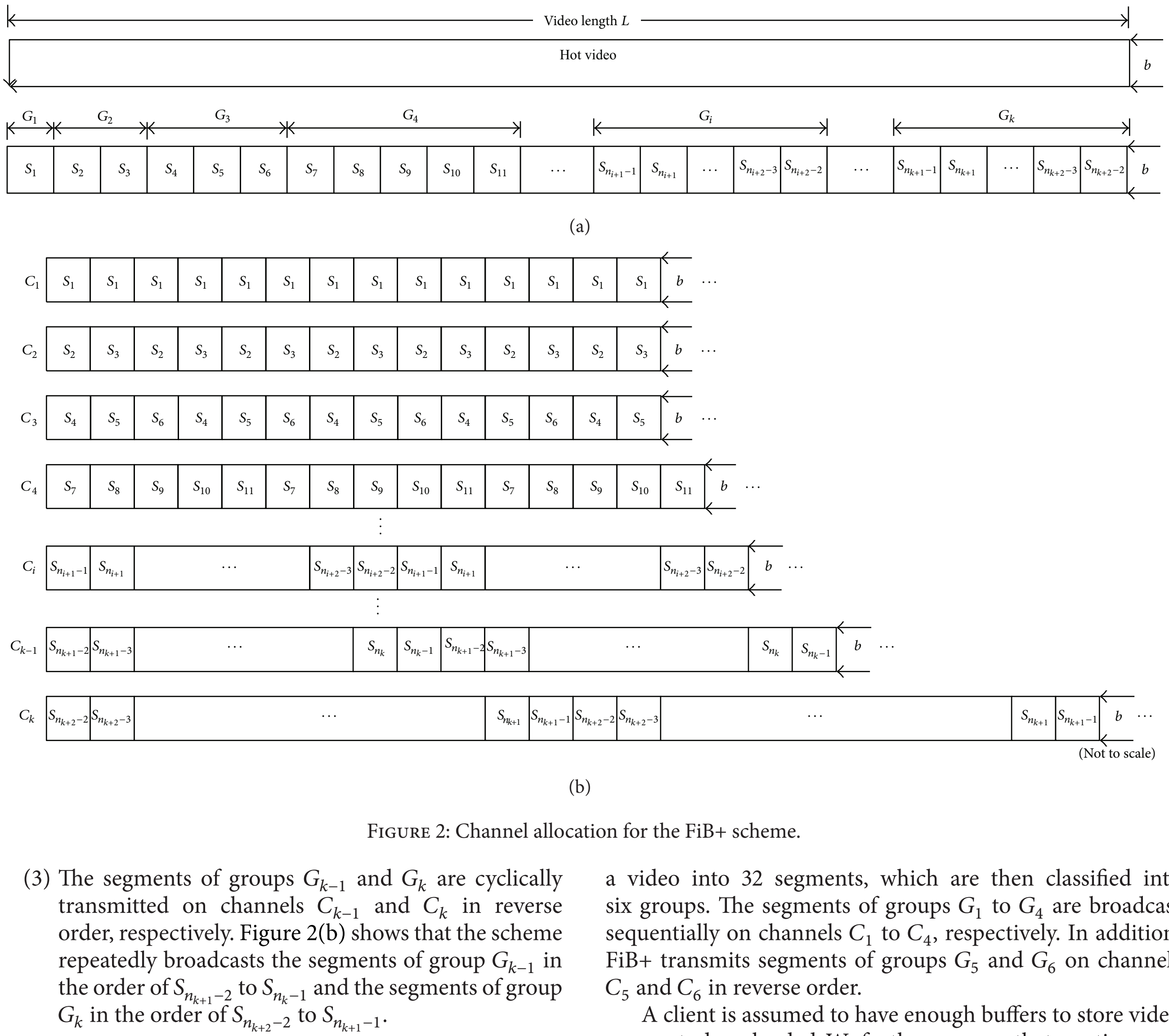


FIGURE 1: Illustration of segment downloading for the FiB scheme, where $k = 6$.



Video length L
Hot video
b
G_1 G_2 G_3 G_4 G_i G_k
(a)
C_1 C_2 C_3 C_4 C_i C_{k-1} C_k
(Not to scale)
(b)

FIGURE 2: Channel allocation for the FiB+ scheme.

(3) The segments of groups G_{k-1} and G_k are cyclically transmitted on channels C_{k-1} and C_k in reverse order, respectively. Figure 2(b) shows that the scheme repeatedly broadcasts the segments of group G_{k-1} in the order of $S_{n_{k+1}-2}$ to S_{n_k-1} and the segments of group G_k in the order of $S_{n_{k+2}-2}$ to $S_{n_{k+1}-1}$.

Figure 3 demonstrates the segment broadcasting and downloading for FiB+, where the segments downloaded and played by a client are gray. Let T_0 be the time that the client starts receiving video segments and be the origin (i.e., the first time unit) of the time axis. Due to $k = 6$, FiB+ equally divides a video into 32 segments, which are then classified into six groups. The segments of groups G_1 to G_4 are broadcast sequentially on channels C_1 to C_4, respectively. In addition, FiB+ transmits segments of groups G_5 and G_6 on channels C_5 and C_6 in reverse order.

A client is assumed to have enough buffers to store video segments downloaded. We further suppose that one time unit equals the length of a segment throughout this study. Playing a video on the client side includes the following steps.

(1) Download segments of group G_i on channel C_i during time units n_{i-1} to $n_{i-1} + n_i - 1 = n_{i+1} - 1$, where

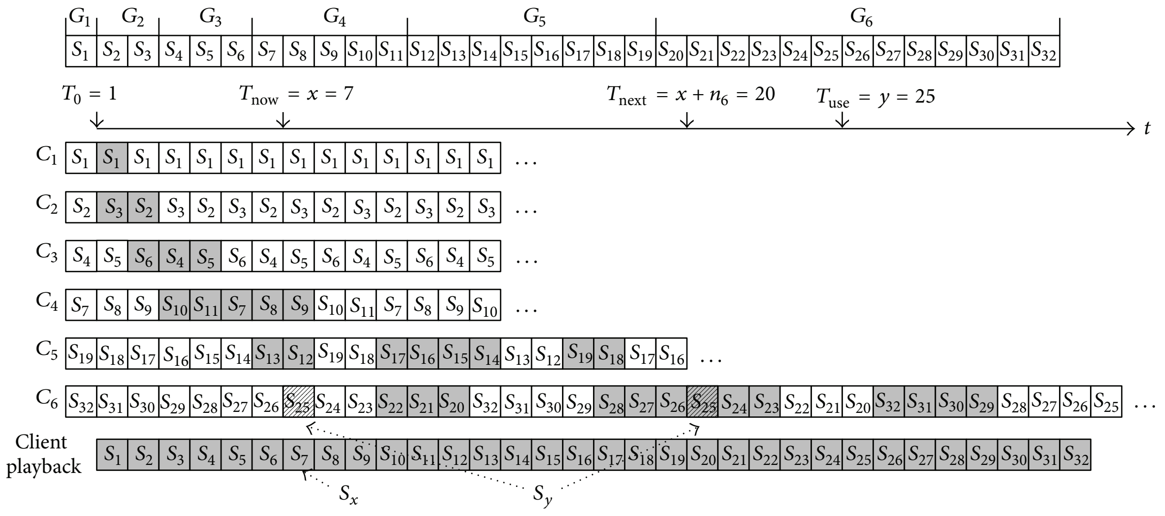

G_1 G_2 G_3 G_4 G_5 G_6
$T_0 = 1$
$T_{\text{now}} = x = 7$
$T_{\text{next}} = x + n_6 = 20$
$T_{\text{use}} = y = 25$
t
C_1 C_2 C_3 C_4 C_5 C_6
Client playback
S_x
S_y

FIGURE 3: Illustration of segment broadcasting and downloading for the FiB+ scheme, where $k = 6$ and $N = 32$.

$1 \le i \le k-2$ and $n_0 = 1$. For example, the client accepts segments from channel C_4 during time units $n_{4-1} = 3$ to $n_{4+1} - 1 = 7$, as shown in Figure 3.

(2) The paper next presents how a client receives segments from channels C_{k-1} and C_k. (In Figure 3, refer to channels C_5 and C_6.) Suppose that a client first sees a segment S_y on a channel C_i at time T_{now} and sees the next segment S_y at time T_{next}, where $i = k-1$ or $i = k$. (In Figure 3, $i = 6$ and $y = 25$.) The client is also assumed to play segments S_x and S_y at time T_{now} and T_{use}, respectively. Clearly, if $T_{\text{next}} \le T_{\text{use}}$, the client can delay downloading segment S_y at time T_{now}, without interrupting the playback. Substituting $T_{\text{use}} = y$th time unit, $T_{\text{now}} = x$th time unit, and $T_{\text{next}} = T_{\text{now}} + n_i$ into $T_{\text{next}} \le T_{\text{use}}$, we obtain

$$x + n_i \le y. \tag{3}$$

If the inequality is true, the client does not receive segment S_y at time T_{now}, otherwise, performs the downloading immediately. For instance, when the client first sees segment S_{25} with only diagonal lines on channel C_6 at the 7th time unit (i.e., T_{now}) in Figure 3, (3) is true, $7 + 13 \le 25$, and the client does not download the segment. Afterwards, the client sees next segment S_{25} with gray color and diagonal lines at the 20th time unit. The client must receive the segment because (3) does not hold, $20 + 13 > 25$.

(3) The client plays the video in the order of $S_1, S_2, \ldots, S_N$ at time T_0.

(4) The client stops loading data from networks when all the segments have been received.

FiB+ and FiB differ in three areas.

(i) *Equal-length segment partition versus variable-length segment partition*. FiB+ divides a video into multiple equal-length segments, while FiB partitions a video into variable-length segments. For example, given $k = 6$, FiB divides a video into six segments, whose lengths are $L/32$, $2L/32$, $3L/32$, $5L/32$, $8L/32$, and $13L/32$. On the other hand, FiB+ partitions a video into 32 segments, whose lengths all equal $L/32$.

(ii) *Multiple segments on each channel versus single segment*. FiB+ cyclically broadcasts several segments on each channel except the first channel, and FiB transmits only one.

(iii) *Segment transmission in reverse order*. The FiB+ scheme broadcasts segments on the last two channels in reverse order. For example, the scheme transmits segments S_{19} to S_{12} on channel C_5 and segments S_{32} to S_{20} on channel C_6, as illustrated in Figure 3.

3.1. Analysis of Segment Playing and Downloading on a Single Channel. We next analyze the segment downloading on channel C_i, where $1 \le i \le k$.

For $1 \le i \le k-2$, a client receives segments $S_{n_{i+1}-1}$ to $S_{n_{i+2}-2}$ from channel C_i during time units n_{i-1} to $n_{i+1}-1$ and plays the segments during time units $n_{i+1} - 1$ to $n_{i+2} - 2$, as mentioned previously. Suppose that a client sees a segment S_j at the $(n_{i+1}-1)$th time unit, where $n_{i+1}-1 \le j \le n_{i+2}-2$. Figure 4(a) shows how a client downloads and plays segments, where the segments downloaded and played by the client are gray.

For $i = k-1$ or k, a client downloads segments according to (3). We also assume that a client sees a segment S_j at the $(n_{i+1}-1)$th time unit, where $n_{i+1}-1 \le j \le n_{i+2}-2$. A complete segment-downloading diagram for channel C_i is based on (3), as indicated in Figure 4(b). The explanation is as follows.

The client always downloads segment S_j since the inequality of (3) does not hold for $x = n_{i+1} - 1$ and $y = j$ (i.e., $n_{i+1} - 1 + n_i = n_{i+2} - 1 > j$). In addition, because the segments of group G_i are transmitted once on channel C_i every n_i time units and are played during time units $n_{i+1} - 1$

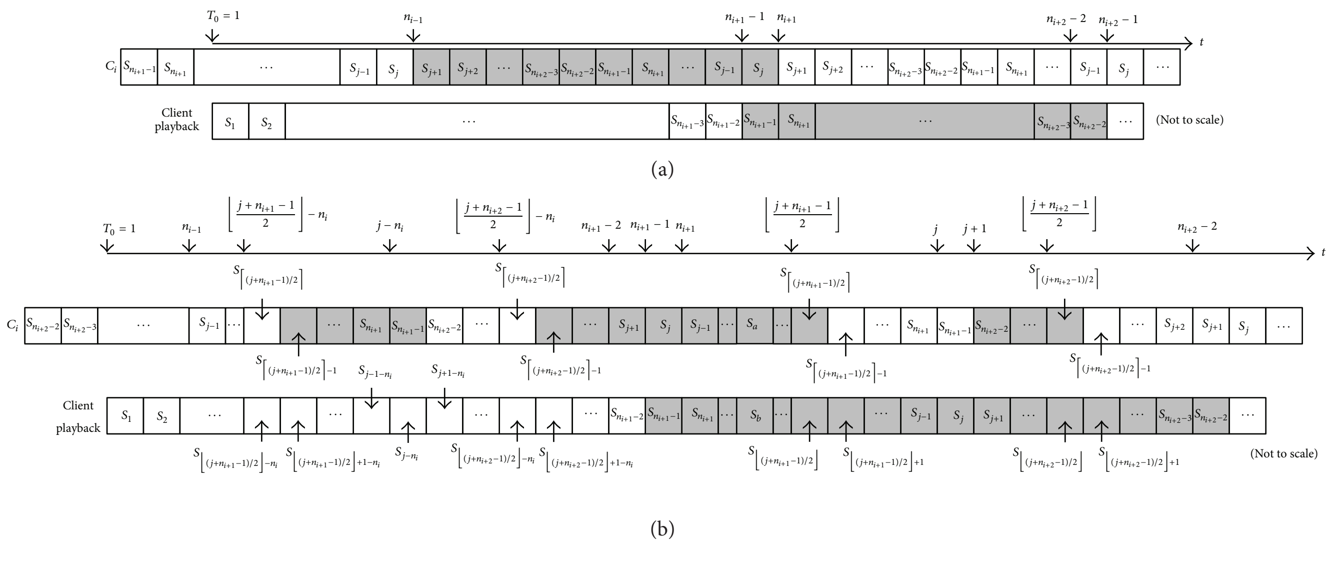


FIGURE 4: Segment downloading on channel C_i for FiB+.

to $n_{i+2} - 2$, the client downloads a segment of group G_i either during time units $n_{i+1} - 1$ to $n_{i+2} - 2$ or during time units n_{i-1} to $n_{i+1} - 2$ (i.e., before the downloading of segment S_j).

3.1.1. Segment Downloading within $[n_{i+1}-1, n_{i+2}-2]$. Figure 4(b) shows that segments $S_{n_{i+1}-1}$ to S_j are broadcast on channel C_i in descending order during time units $n_{i+1} - 1$ to j, while a client plays these segments in turn. Let S_a be a segment broadcast on channel C_i during this period, and let S_b be the client-playback segment corresponding to S_a. Clearly, if $a \geq b$, a client must download segment S_a to ensure continuous playing. Because the number of segments between S_j and S_a on channel C_i equals the number of segments between $S_{n_{i+1}-1}$ and S_b on the client playback, $j - a = b - (n_{i+1} - 1)$ and $a = j + n_{i+1} - 1 - b$. Substituting this equation to $a \geq b$ yields $(j + n_{i+1} - 1)/2 \geq b$. The maximum value of b is $\lfloor (j + n_{i+1} - 1)/2 \rfloor$, and the corresponding value of a equals $j + n_{i+1} - 1 - \lfloor (j + n_{i+1} - 1)/2 \rfloor = \lceil (j + n_{i+1} - 1)/2 \rceil$. Figure 4(b) illustrates that the client downloads segments S_j to $S_{\lceil (j+n_{i+1}-1)/2 \rceil}$ during time units $n_{i+1} - 1$ to $\lfloor (j + n_{i+1} - 1)/2 \rfloor$ and does not download any segment during time units $\lfloor (j + n_{i+1} - 1)/2 \rfloor + 1$ to j. Similarly, this study obtains that a client receives segments $S_{n_{i+2}-2}$ to $S_{\lceil (j+n_{i+2}-1)/2 \rceil}$ during time units $j + 1$ to $\lfloor (j + n_{i+2} - 1)/2 \rfloor$ and does not download any segment during time units $\lfloor (j + n_{i+2} - 1)/2 \rfloor + 1$ to $n_{i+2} - 2$.

3.1.2. Segment Downloading within $[n_{i-1}, n_{i+1}-2]$. From (3), the client must download segments $S_{\lceil (j+n_{i+2}-1)/2 \rceil - 1}$ to S_{j+1} during time units $\lfloor (j + n_{i+2} - 1)/2 \rfloor + 1 - n_i$ to $n_{i+2} - 2 - n_i = n_{i+1} - 2$ because the client does not download these segments during time units $\lfloor (j + n_{i+2} - 1)/2 \rfloor + 1$ to $n_{i+2} - 2$, as shown in Figure 4(b). The figure further indicates that the client does not accept segments $S_{n_{i+2}-2}$ to $S_{\lceil (j+n_{i+2}-1)/2 \rceil}$ during time units $j + 1 - n_i$ to $\lfloor (j + n_{i+2} - 1)/2 \rfloor - n_i$ since the client will perform their downloading during time units $j + 1$ to $\lfloor (j + n_{i+2} - 1)/2 \rfloor$. Similarly, the client must receive segments $S_{\lceil (j+n_{i+1}-1)/2 \rceil - 1}$ to $S_{n_{i+1}-1}$ during time units $\lfloor (j + n_{i+1} - 1)/2 \rfloor + 1 - n_i$ to $j - n_i$ because the client does not download these segments during time units $\lfloor (j + n_{i+1} - 1)/2 \rfloor + 1$ to j. Furthermore, since the client will download segments S_{j-1} to $S_{\lceil (j+n_{i+1}-1)/2 \rceil}$ during time units n_{i+1} to $\lfloor (j + n_{i+1} - 1)/2 \rfloor$, the client does not load any segment during time units $n_{i+1} - n_i = n_{i-1}$ to $\lfloor (j + n_{i+1} - 1)/2 \rfloor - n_i$, as illustrated in Figure 4(b).

3.2. Workable Verification. This section shows that FiB+ guarantees continuous playback and two-channel bandwidth demand on the client side.

3.2.1. Continuous Playback. To keep on-time video delivery, the study in [7] indicates that a video server must broadcast a segment S_j on a channel C_i at least once in every j time units. For FiB+, a server transmits a segment S_j once every n_i time units, where $n_{i+1} - 1 \leq j \leq n_{i+2} - 2$. This paper thus needs to prove $j \geq n_i$. We then evaluate

$$\begin{aligned} j - n_i &\geq (n_{i+1} - 1) - n_i, \quad \text{due to } n_{i+1} - 1 \leq j \\ &= n_{i-1} - 1 \\ &\geq 0. \end{aligned} \tag{4}$$

For FiB+, the segment broadcasting frequency is large enough to let clients receive video data in time.

3.2.2. Two-Channel Bandwidth Demand. From the previous analysis in Figure 4, we make a temporal-channel map of segment downloading for each channel, as indicated in Figure 5. In this figure, segments downloaded and played by a client are gray. This work divides client playback time t (in terms of time units) into multiple successive durations for ease of explanation.

For $T_0 \leq t \leq n_{k-2} - 1$, the client merely receives segments from channels C_1 to C_{k-2} because the client starts the segment

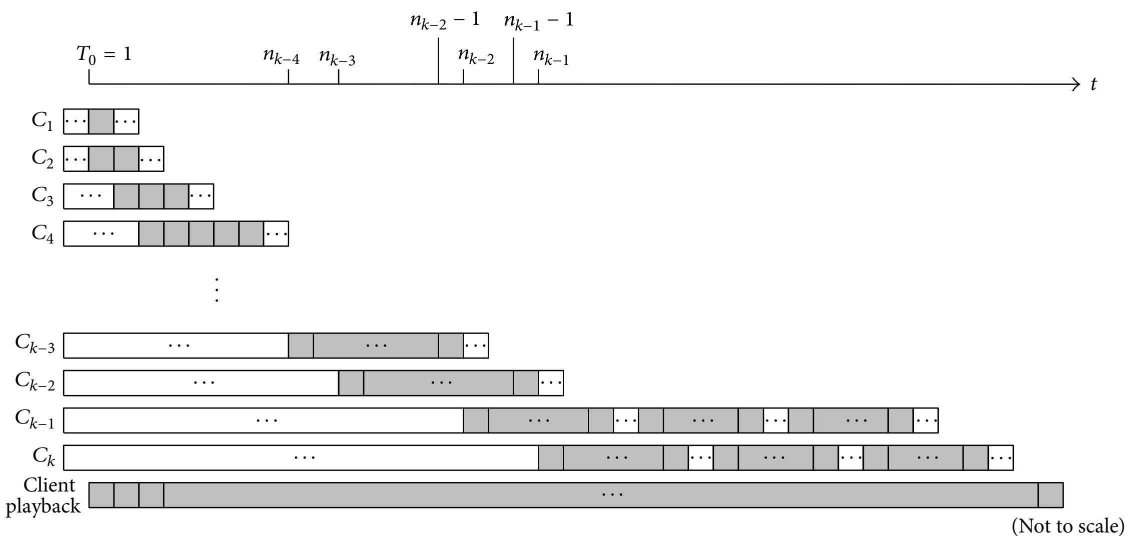


FIGURE 5: Segment downloading using client bandwidth $2b$.

downloading on channel C_{k-1} at time unit n_{k-2}, as shown in Figure 5. According to Step 1 of segment downloading on the client side, the client uses two-channel bandwidth to load segments in this period.

For $n_{k-2} \le t \le n_{k-1} - 1$, the client receives segments only from channels C_{k-2} and C_{k-1} because the client finishes receiving segments from channel C_1 to C_{k-3} before time unit n_{k-2} and starts downloading segments on channel C_k at time unit n_{k-1}, as indicated in Figure 5.

For $n_{k-1} \le t$, the client simply receives the remaining segments from channels C_{k-1} and C_k because the segment downloading on channel C_{k-2} completes at time unit $n_{k-1}-1$.

Accordingly, an FiB+ client can download segments using two-channel bandwidth.

4. Performance Analysis and Comparison

When a client just misses segment S_1 of a requested video, the maximum waiting time δ equals the access time of the segment from the first channel. Thus, $\delta = L/N = L/\sum_{p=1}^{k} n_p$, the same as that of FiB. According to the previous studies [15, 17], this work has calculated the values of N offered by these schemes at different numbers of channels, as listed in Table 2. The larger the value is, the smaller the waiting time is. The table reveals that FiB and FiB+ yield far bigger values than other schemes. Figure 6 shows maximum waiting time versus server channels. FiB and FiB+ thus achieve much smaller waiting time than SkB and CCA+ under two-channel client bandwidth. For example, when the server bandwidth equals 10 channels, FiB and FIB+ reduce the broadcast latency to less than 32 seconds. By contrast, SkB and CCA+ incur more than 51 and 48 seconds, respectively.

Before analyzing the entire buffer requirements, we first investigate the number of the buffered segments when a client performs segment downloading on a single channel C_i.

Lemma 1. *Let $B(i,t)$ be the function of the number of the segments buffered by an FiB+ client on channel C_i at the tth time unit.*

For $1 \le i \le k-2$,

$$\begin{cases} B(i,t) = 0, & t < n_{i-1}, \\ B(i,t) = t - n_{i-1} + 1, & n_{i-1} \le t \le n_{i+1} - 2, \\ B(i,t) = n_{i+2} - 2 - t, & n_{i+1} - 2 < t \le n_{i+2} - 2, \\ B(i,t) = 0, & n_{i+2} - 2 < t. \end{cases} \tag{5a}$$

For $i = k-1$ or k,

$$\begin{cases} B(i,t) = 0, & t < n_{i-1}, \\ B(i,t) \le \left\lfloor \dfrac{t - n_{i-1} + 2}{2} \right\rfloor, & n_{i-1} \le t \le n_{i+1} - 2, \\ B(i,t) \le \left\lfloor \dfrac{n_i}{2} \right\rfloor, & n_{i+1} - 2 < t \le n_{i+2} - 2 - \left\lceil \dfrac{n_i}{2} \right\rceil, \\ B(i,t) \le n_{i+2} - 2 - t, & n_{i+2} - 2 - \left\lceil \dfrac{n_i}{2} \right\rceil < t \le n_{i+2} - 2, \\ B(i,t) = 0, & n_{i+2} - 2 < t. \end{cases} \tag{5b}$$

Proof. See Appendix B. □

Equation (5b) shows that a client buffers at most $\lfloor n_i/2 \rfloor$ segments from channel C_i for $i = k-1$ or k. On the other hand, an FiB client needs to buffer $n_i - 1$ segments [18]. Such a difference leads to the result that FiB+ requires much smaller buffering space.

Theorem 2. *Let $B(t)$ be the maximum number of segments buffered by an FiB+ client. Then, $B(t) \le \lceil n_{k-1}/4 \rceil + \lfloor n_k/2 \rfloor$.*

Proof. See Appendix C. □

Due to $\lim_{i\to\infty}(n_{i+1}/n_i) \approx ((1+\sqrt{5})/2)$ [22] and $N = n_{k+2} - 2$, $\lim_{k\to\infty}((\lceil n_{k-1}/4 \rceil + \lfloor n_k/2 \rfloor)/N) \approx 0.25$. This result

TABLE 2: The values of N offered by different schemes.

k	1	2	3	4	5	6	7	8	9	10
FiB/FiB+	1	3	6	11	19	32	53	87	142	231
SkB	1	3	5	10	15	27	39	64	89	141
CCA+2	1	3	5	10	15	27	39	64	89	149

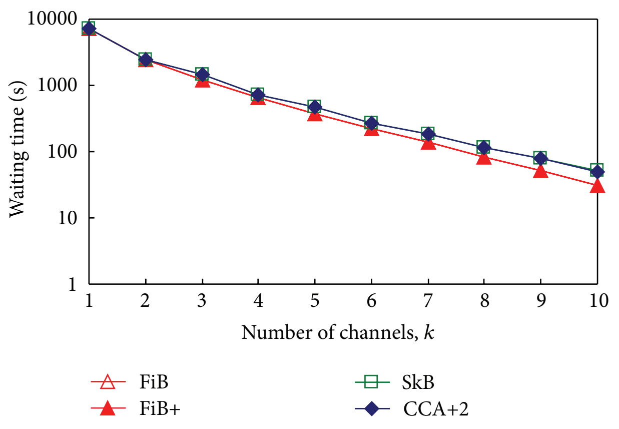


FIGURE 6: Maximum waiting time incurred on new clients at different numbers of channels (L = 120 minutes).

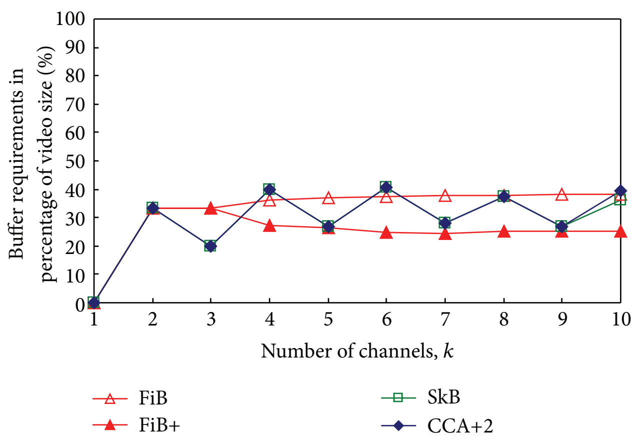


FIGURE 7: Comparison of required buffers.

indicates that an FiB+ client can buffer only 25% of video size, like RFB. We used the Perl language to implement a simulator, which could estimate the buffer requirements for FiB+. The results are listed in Table 3. The buffer size required by FiB+ is quite close to the bound when $k \geq 6$. Because FiB has to buffer $n_k - 1$ segments, we can derive the buffer reduction rate of FiB+ versus FiB as follows: $\lim_{k\to\infty}(1 - (\lceil n_{k-1}/4\rceil + \lfloor n_k/2\rfloor)/(n_k - 1)) \approx 0.345$. FiB+ can reduce buffer requirements by 34.5%, when compared with FiB. Table 3 shows that with the growth of k, the reduction rate is close to the bound. For example, for $k = 10$, an FiB client buffers 38.1% of video size. By contrast, an FiB+ client buffers only 25.1%. The reduction rate is 34.1%. According to the previous studies [15, 17], this work presents the buffer sizes required by different broadcasting schemes at different numbers of server channels, as indicated in Figure 7. For $k > 3$, the FiB+ scheme outperforms all the schemes.

5. Conclusions

With the advance of mobile computing technology, many clients access VOD services through their mobile devices. Delivering videos under rather restricted client resources is increasingly important. To fulfill this requirement, several schemes, such as SkB, FiB, and CCA+, are proposed to allow a client to watch a video using two-channel bandwidth. Extending FiB, this work devises FiB+, which exhibits the merits of small client waiting time and buffering space. The scheme still guarantees on-time video delivery under two-channel receiving bandwidth. According to the performance analysis, FiB+ yields the minimum waiting time and requires smaller client buffer size, when compared with most existing schemes.

Appendices

A. Proof of Equation (2)

For $i \bmod 2 = 1$, let $i = 2q + 1$. Then,

$$\begin{aligned}\sum_{p=1}^{i} n_p &= n_1 + n_2 + n_3 + n_4 + \cdots + n_i \\ &= n_3 + n_5 + \cdots + n_{2q+1} + n_{2q+1}, \quad \text{from (1)} \\ &= n_2 + n_3 + n_5 + \cdots + n_{2q+1} + n_{2q+1} - n_2 \\ &= n_4 + n_5 + \cdots + n_{2q+1} + n_{2q+1} - n_2, \quad \text{from (1)} \\ &= n_{2q+2} + n_{2q+1} - n_2, \quad \text{from (1)} \\ &= n_{2q+3} - n_2, \quad \text{from (1)} \\ &= n_{i+2} - 2.\end{aligned} \tag{A.1}$$

For $i \bmod 2 = 0$, let $i = 2q$. Then,

$$\begin{aligned}\sum_{p=1}^{i} n_p &= n_1 + n_2 + n_3 + n_4 + \cdots + n_i \\ &= n_3 + n_5 + \cdots + n_{2q+1}, \quad \text{from (1)} \\ &= n_2 + n_3 + n_5 + \cdots + n_{2q+1} - n_2 \\ &= n_4 + n_5 + \cdots + n_{2q+1} - n_2, \quad \text{from (1)}\end{aligned}$$

$$\begin{aligned} &= n_{2q+2} - n_2, \quad \text{from (1)} \\ &= n_{i+2} - 2. \end{aligned} \tag{A.2}$$

Accordingly, $\sum_{p=1}^{i} n_p = n_{i+2} - 2$.

B. Proof of Lemma 1

This study first proves (5a). For easy understanding, please refer to Figure 4(a).

(1) For $t < n_{i-1}$, a client downloads no segment on channel C_i because these segments will appear again during time units n_{i-1} to $n_{i+1} - 1$. Thus, $B(i,t) = 0$.

(2) For $n_{i-1} \le t \le n_{i+1} - 2$, a client continuously accepts one segment every time unit but consumes no segment. Thus, the number of buffered segment equals $t - n_{i-1} + 1$. When $t = n_{i+1} - 2$, the client buffers the maximum segments and $B(i,t) = n_i - 1$.

(3) For $n_{i+1} - 2 < t \le n_{i+2} - 2$, Figure 4(a) shows that a client stops loading data but plays the video in this period. The client consumes one segment every time unit, and thus the buffered segments decrease, $B(i,t) = n_i - (t - (n_{i+1} - 2)) = n_{i+2} - 2 - t$.

(4) For $n_{i+2} - 2 < t$, a client has finished playing all the segments on channel C_i, and thus $B(i,t) = 0$.

The proof for (5b) is as follows. For easy understanding, please refer to Figure 4(b).

(1) For $t < n_{i-1}$, a client does not download any segment on channel C_i, and thus, $B(i,t) = 0$.

(2) For $n_{i-1} \le t \le n_{i+1} - 2$, the paper divides the value range of t into four successive subranges for ease of proof.

(a) For $n_{i-1} \le t \le \lfloor (j + n_{i+1} - 1)/2 \rfloor - n_i$, Figure 4(b) shows that the client downloads no segment on channel C_i, and thus $B(i,t) = 0 \le \lfloor (t - n_{i-1} + 2)/2 \rfloor$.

(b) For $\lfloor (j + n_{i+1} - 1)/2 \rfloor - n_i < t \le j - n_i$,

$$\begin{aligned} &B(i,t) \\ &\quad = t - \left(\left\lfloor \frac{j + n_{i+1} - 1}{2} \right\rfloor - n_i \right), \quad \text{see Figure 4(b)} \\ &\quad \le t + n_i - \left\lfloor \frac{(t + n_i) + (n_{i+1} - 1)}{2} \right\rfloor, \quad \text{due to } t \le j - n_i \\ &\quad \le \left\lfloor \frac{t - n_{i-1} + 2}{2} \right\rfloor. \end{aligned} \tag{B.1}$$

(c) For $j - n_i < t \le \lfloor (j + n_{i+2} - 1)/2 \rfloor - n_i$,

$$\begin{aligned} &B(i,t) \\ &\quad = (j - n_i) - \left(\left\lfloor \frac{j + n_{i+1} - 1}{2} \right\rfloor - n_i \right), \quad \text{see Figure 4(b)} \\ &\quad \le \left\lfloor \frac{t - n_{i-1} + 2}{2} \right\rfloor, \quad \text{due to } j - n_i < t. \end{aligned} \tag{B.2}$$

(d) For $\lfloor (j + n_{i+2} - 1)/2 \rfloor - n_i < t \le n_{i+1} - 2$,

$$\begin{aligned} &B(i,t) \\ &\quad = \left(j - \left\lfloor \frac{j + n_{i+1} - 1}{2} \right\rfloor \right) \\ &\qquad + \left(t - \left(\left\lfloor \frac{j + n_{i+2} - 1}{2} \right\rfloor - n_i \right) \right), \quad \text{see Figure 4(b)} \\ &\quad \le \left\lfloor \frac{j + 2t - n_{i+1} + 2 + 2n_i}{2} \right\rfloor - \left\lfloor \frac{j + n_{i+2} - 1}{2} \right\rfloor \\ &\quad \le \left\lfloor \frac{t - n_{i-1} + 2}{2} \right\rfloor, \quad \text{due to } t \le n_{i+1} - 2. \end{aligned} \tag{B.3}$$

Thus, $B(i,t) \le \lfloor n_i/2 \rfloor$ when $t = n_{i+1} - 2$.

(3) For $n_{i+1} - 2 < t \le n_{i+2} - 2 - \lceil n_i/2 \rceil$, the client plays one segment every time unit while downloading at most one segment. The number of buffered segments is not larger than that at time unit $t = n_{i+1} - 2$, and thus $B(i,t) \le \lfloor n_i/2 \rfloor$.

(4) For $n_{i+2} - 2 - \lceil n_i/2 \rceil < t \le n_{i+2} - 2$, the client has played $t - (n_{i+1} - 2)$ segments, and the number of the remaining segments is

$$n_i - (t - (n_{i+1} - 2)) = n_{i+2} - 2 - t. \tag{B.4}$$

Thus, $B(i,t) \le n_{i+2} - 2 - t$.

(5) For $n_{i+2} - 2 < t$, the client finishes playing all the segments on channel C_i so $B(i,t) = 0$.

The proof is complete.

C. Proof of Theorem 2

This work divides client playing time t (in terms of time units) into multiple successive durations for ease of proof.

(1) For $t \le n_{k-2} - 2$, Figure 5 shows that the client simply receives segments from channels C_1 to C_{k-2}. In addition, the client downloads two segments but plays only one every time unit. The number of buffered segments thus increases with time and achieves the maximum at time unit $n_{k-2} - 2$. At this time, the client has finished playing segments from channels C_1 to C_{k-4}, and thus simply buffers segments from channels C_{k-3} and C_{k-2}. Accordingly,

$$\begin{aligned} B(t) &= B(k-3, n_{k-2} - 2) + B(k-2, n_{k-2} - 2) \\ &= ((n_{k-2} - 2) - n_{k-4} + 1) \\ &\quad + ((n_{k-2} - 2) - n_{k-3} + 1), \quad \text{from (5a)} \\ &= n_{k-2} - 2, \quad \text{from (1)} \\ &\le \left\lceil \frac{n_{k-1}}{4} \right\rceil + \left\lfloor \frac{n_k}{2} \right\rfloor. \end{aligned} \tag{C.1}$$

(2) For $n_{k-2} - 2 < t \le n_{k-1} - 2$, the client has finished playing all the segments received from channels C_1 to C_{k-4} and downloads no segment from channel C_k. We thus merely consider the segments on channels C_{k-3} to C_{k-1}. The client downloads at least one segment from channel C_{k-2} but plays

Table 3: Comparison of buffering space in the percentage of video size using k server channels.

k	1	2	3	4	5	6	7	8	9	10
FiB (%)	0	33.3	33.3	36.4	36.8	37.5	37.7	38	38	38.1
FiB+ (%)	0	33.3	33.3	27.3	26.3	25	24.5	25.3	25.4	25.1
Reduction rate (%)	0	0	0	25	28.6	33.3	35	33.3	33.3	34.1

only one every time unit. Thus, the maximum number of buffered segments appears at time unit $n_{k-1}-2$ as follows:

$$\begin{aligned} B(t) &= B(k-3, n_{k-1}-2) + B(k-2, n_{k-1}-2) \\ &\quad + B(k-1, n_{k-1}-2) \\ &\le n_{k-2} - 1 + \left\lfloor \frac{(n_{k-1}-2) - n_{k-2} + 2}{2} \right\rfloor, \\ &\qquad \text{from (5a) and (5b)} \\ &= n_{k-2} + \left\lfloor \frac{n_{k-3}}{2} \right\rfloor - 1 \\ &\le \left\lceil \frac{n_{k-1}}{4} \right\rceil + \left\lfloor \frac{n_k}{2} \right\rfloor. \end{aligned} \tag{C.2}$$

(3) For $n_{k-1}-2 < t \le n_k-2$, the client has finished playing all the segments received from channels C_1 to C_{k-3}, and thus the client only buffers segments from channels C_{k-2} to C_k as follows:

$$\begin{aligned} B(t) &= B(k-2,t) + B(k-1,t) + B(k,t) \\ &\le n_k - 2 - t + \left\lfloor \frac{t-n_{k-2}+2}{2} \right\rfloor + \left\lfloor \frac{t-n_{k-1}+2}{2} \right\rfloor, \\ &\qquad \text{from (5a) and (5b)} \\ &\le \left\lceil \frac{n_{k-1}}{4} \right\rceil + \left\lfloor \frac{n_k}{2} \right\rfloor. \end{aligned} \tag{C.3}$$

(4) For $n_k - 2 < t \le n_{k+1} - 2 - \lceil n_{k-1}/2 \rceil$, the client has finished playing all the segments received from channels C_1 to C_{k-2} and only performs segment downloading on channels C_{k-1} and C_k as follows:

$$\begin{aligned} B(t) &\le B(k-1,t) + B(k,t) \\ &\le \left\lfloor \frac{n_{k-1}}{2} \right\rfloor + \left\lfloor \frac{t-n_{k-1}+2}{2} \right\rfloor, \quad \text{from (5b)} \\ &\le \left\lceil \frac{n_{k-1}}{4} \right\rceil + \left\lfloor \frac{n_k}{2} \right\rfloor, \quad \text{due to } t \le n_{k+1} - 2 - \left\lceil \frac{n_{k-1}}{2} \right\rceil. \end{aligned} \tag{C.4}$$

(5) For $n_{k+1} - 2 - \lceil n_{k-1}/2 \rceil < t \le n_{k+1} - 2$, similarly, the client merely downloads segments on channels C_{k-1} and C_k as follows:

$$\begin{aligned} B(t) &\le B(k-1,t) + B(k,t) \\ &\le n_{k+1} - 2 - t + \left\lfloor \frac{t-n_{k-1}+2}{2} \right\rfloor, \quad \text{from (5b)} \\ &\le \left\lceil \frac{n_{k-1}}{4} \right\rceil + \left\lfloor \frac{n_k}{2} \right\rfloor, \quad \text{due to } n_{k+1} - 2 - \left\lceil \frac{n_{k-1}}{2} \right\rceil < t. \end{aligned} \tag{C.5}$$

(6) For $n_{k+1} - 2 < t$, the client simply performs data downloading on channel C_k, and thus $B(t) = B(k,t)$. From (5b), $B(t) = B(k,t) \le \lfloor n_k/2 \rfloor \le \lceil n_{k-1}/4 \rceil + \lfloor n_k/2 \rfloor$.

The proof is complete.

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