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A note on on-line broadcast scheduling with deadlines

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1. Introduction

Broadcasting technologies receive a lot attention on networks that employs broadcasting to disseminate data or information. In contract to the traditional point-to-point mode of communication, broadcasting technologies have an advantage that one broadcast by the server can simultaneously satisfy requests required from multiple clients for an identical message. In this paper, we focus a pull-based model of broadcast scheduling problems, which is formalized as below.

Problem description. There is a collection of pages $S = \{1, \ldots, n\}$, in the server. The clients send requests to ask for these pages and each request has a release time, deadline and a distinct page to ask for. The server answers requests by broadcasting pages. Note that a broadcast of a page can satisfy all the requests asking for the same page simultaneously and there is at most one page to be broadcasted at any time During broadcasting, the preemption is allowed, but if the broadcast of a page is preempted, then in case the server choose this page to broadcast again, it must from the start point not the break point, we call this as preemption with restart. When the request for the page that currently broadcast arrives it must be kept in the queue of unsatisfied requests.

In this paper, we study an on-line broadcast scheduling problem with deadlines, in which the requests asking for the same page can be satisfied simultaneously by broadcasting this page, and every request is associated with a release time, deadline and a required page with a unit size. The objective is to maximize the number of requests satisfied by the schedule. In this paper, we focus on an important special case where all the requests have their spans (the difference between release time and deadline) less than 2. We give an optimal online algorithm, i.e., its competitive ratio matches the lower bound of the problem.

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Algorithm 1. Weighting Pages (WP)

1: Initialize the profit $W$, i.e., $W \leftarrow 0$.
2: while (request-arrival or broadcast-completion) do
3:   \{ 
4:     request-arrival: Put new requests into the pending list.
5:     if $W(P_j, t) \geq 2 - W$ then
6:       Aborted page $P_j$, go to selection step (including the case $P_a = P_j$).
7:     end if
8:     broadcast-completion: Remove the requests satisfied, go to selection step if the pending list is not empty.
9:   \}
10: Select: A page $P$ such that $W(P, t)$ is maximized (break a tie arbitrarily), and broadcast the page $P$ and $W \leftarrow W(P, t)$, where $t$ is the current time.

To broadcast a page, the page with the maximal weight is selected to be served; (ii) when a new request for page $P_a$ arrives if to start broadcasting page $P_a$ can double the profit (i.e., throughput), then we abort broadcasting the current page, and put the new request into a pending list and select a page with the maximal weight and broadcast that page (this is the difference between our algorithm and the ones in [5,10]). Otherwise, continue to broadcast the current page and put the new request in the pending list.

Let $P_a$ be the page of a new request which arrives at the current time $t$, let $P_c$ denote the currently broadcast page if it exists. Our algorithm is described (see Algorithm 1).

We first define a concept called basic chain and observe an important property related to it. Then, we divide the broadcasts by our algorithm into a set of basic chains and combine the property to get an upper bound 4 for the competitive ratio.

Definition 4 (Basic chain). For $i \leq j$, a sequence of broadcasts $(P_i, P_{i+1}, \ldots, P_j)$ is called a basic chain if pages $P_i, \ldots, P_{j-1}$ are aborted broadcasts and page $P_j$ is a completed broadcast, and the broadcast just before $P_j$ is empty or a completed broadcast.

Theorem 1. For any input list of requests with laxity less than 2, the competitive ratio of our algorithm is 4.

Proof. Let the sequence of broadcasts $(P_1, P_2, \ldots, P_j)$ be the first basic chain generated by our on-line algorithm. Let $(P^*_1, P^*_2, \ldots, P^*_m)$ be the first pages broadcast by an optimal scheduling such that the starting point of broadcasting page $P^*_m$ is sat in the time interval for broadcasting page $P_j$, shown as Fig. 1 (if $P^*_m$ does not exist, then we set $P^*_m$ as a dummy page). Let time $t_i$ ($t^*_i$) denote the starting point of broadcasting page $P_i$ ($P^*_i$) for $1 \leq i \leq m$ Without loss of generality, assume that $(t^*_i - t_i) \geq 1$ for $1 \leq i \leq m$ otherwise we can get another optimal schedule by broadcasting $P^*_i$ at time $t^*_i$ except for page $P^*_j$ and doing nothing during $[t^*_j, t^*_{j+1})$.

Now, for $1 \leq i \leq j$, we define a set of intervals, $I_i = [t_i, t_{i+1})$, where $t_{i+1} = t_j + 1$. For an input list $L$, let $A(L)$ and $OPT(L)$ be the number of requests satisfied by our algorithm and an optimal schedule respectively. For $1 \leq i \leq m$, let $x_i^*$ be the number of requests which are satisfied by broadcasting page $P^*_i$ in the optimal schedule.

<table>
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<th>$d-t$</th>
<th>$(-\infty, 1)$</th>
<th>$[1, +\infty)$</th>
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<tr>
<td>Weight</td>
<td>$0$</td>
<td>$1$</td>
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Remember that the whole sequence of broadcasts \((P_1, P_2, \ldots, P_j)\) by our algorithm is a basic chain. Then we have the following observation.

**Claim 1.** For \(1 \leq i \leq m\), \(x^i \leq 2^{i+1-m}W\), where \(W = W(P, t_j)\).

**Proof.** Recall that \(t^i\) is the start time to broadcast page \(P_i\). For \(1 \leq i \leq m\), we have

\[
(t^i - t^i_{i-1}) \geq 1. 
\]

(1)

On the other hand, the whole sequence of broadcasts \((P_1, P_2, \ldots, P_j)\) by our algorithm is a basic chain, by the definition of a basic chain, for \(1 \leq i \leq j\) we have

\[
t_{i+1} - t_i \leq 1. 
\]

(2)

Let \(I_j = [t_j, t_{j+1}]\) be the interval such that \(t^i \in I_j\). By (1) and (2), we have the number of broadcasts during \([t_j, t_{j+1}]\) by our algorithm is not less than the number by the optimal schedule during \([t^i, t^i_{i-1}]\), i.e.,

\[
(j - f) \geq (m - i) \implies f \leq j - (m - i) = j + i - m. 
\]

(3)

According to algorithm WP, for any page \(P\), we have

\[
W(P, t_f) \leq 2^{f-j}W(P_j, t_j) = 2^{f-j}W. 
\]

(4)

Let \(t^i_f\) be the time when the last request for page \(P^i\) released at or before time \(t^i_f\) in the input list. Let \(t^i_f = \max(t_f, t^i_f)\). According to algorithm WP, at time \(t^i_f\) there is a comparison between \(W(P^i, t^i_f)\) and \(W(P, t_f)\). Since page \(P^i\) is broadcast at time \(t^i_f\) by our algorithm, we have

\[
W(P^i, t^i_f) < 2W(P, t_f). 
\]

(5)

By inequalities (3)-(5), we have

\[
W(P^i, t^i_f) \leq 2^{i+1-m}W. 
\]

(6)

Let \(x^i\) be the number of requests for page \(P^i\) which are alive at time \(t^i_f\). By the definition of \(x^i\) and \(t^i_f \leq t^i_{i-1}\), we have

\[
x^i \leq x_i^j. 
\]

(7)

By (7) and (6),

\[
x^i \leq W(P^i, t^i_f) \leq 2^{i+1-m}W. 
\]

(8)

Next we are going to bound \(OPT(L)\), i.e., the throughput by the optimal schedule. Without loss of generality, broadcasts generated by our algorithm and the optimal algorithm looks like Fig. 1.

We prove this theorem by mathematical induction over the number of basic chains produced by our algorithm.

First, we prove that the theorem holds if the whole broadcast generated by algorithm WP is a basic chain. Then we assume that the theorem holds for the case in which there are \(h\) basic chains. Finally, we prove that the theorem still holds for \((h+1)\) basic chains.

**Step 1.** There is only one basic chain in the whole broadcast generated by our algorithm. In this case, we prove \(P^m\) is the last page in the optimal schedule. Otherwise there is at least one request alive at time \(t^m + 1\), where \(t^m \geq t_j\). Since all the requests have laxity less than 2, the alive request must be released after \(t_j\). So, the request would have been broadcasted by our algorithm after \(t_j + 1\). But, this contradicts with the fact that the whole sequence of broadcasts \((P_1, P_2, \ldots, P_j)\) generated by our algorithm is one basic chain. So page \(P^m\) is the last page in the optimal schedule. By Claim 1, we have

\[
OPT(L) = \sum_{i=1}^{m} x^i \leq \sum_{i=1}^{m} 2^{i+1-m}W
\]

\[
= 4W \sum_{i=0}^{m-1} 2^i \leq 4W = 4A(L).
\]

**Step 2.** Assume that this theorem holds when there are \(h\) basic chains in the whole broadcast generated by our algorithm, where \(h \geq 1\). Next we consider the case in which there are \(h + 1\) basic chains in our broadcast. First, we define four sublist of requests. We define \(L_2\) as the sublist of requests that will be considered by our algorithm after time \(t_j + 1\), i.e., the sublist of requests with release time at least \(t_j + 1\) or requests which are still alive at time \(t_j + 1\) \((t^m + 1)\) and not satisfied by our algorithm before \(t_j + 1\). In the same way, we define \(L_2^*\) as the sublist of requests that will be considered by the optimal schedule after \(t^m + 1\), i.e., \(L_2^*\) is the sublist of requests with release time at least \((t^m + 1)\) or requests which are still alive at time \(t^m + 1\) and not satisfied by the optimal algorithm before \(t^m + 1\). Let \(L_2 = L - L_2^*\) and \(L_2^* = L - L_2\). By definitions, \(L_1\) is the sublist of requests with release time before \(t_j + 1\) and not alive at time \(t_j + 1\), i.e., requests with release time before \(t_j + 1\) and not satisfied, or requests satisfied before \(t_j + 1\). Observe that for any request \(R \in L_1\), if request \(R\) is not satisfied by algorithm WP, then request \(R\) is not alive at time \(t_j + 1\), therefore \(R\) is not alive at time \(t^m + 1\) too, where \(t^m \geq t_j\). Then \(R \notin L_2\). If request \(R\) is satisfied by algorithm WP before \(t_j + 1\), then it is not alive at time \(t^m + 1\) since every request has laxity less than 2. So, in both cases, we have \(R \notin L_2^*\), where \(R \in L_1\). Then

\[
L_2^* \subseteq L_2 = L - L_1.
\]

(9)

To estimate the throughput by algorithm WP and the optimal algorithm, we need to modify \(L_2\) and \(L_2^*\) slightly. For every request in \(L_2\), \(x^i \in L_2^*\), if its release time is at least
$t_j + 1$ then just copies it into $L^*_2$ else modifies its release time to $t_j + 1$ then copies it into $L^*_2$. For every request in $L^*_2$, if its release time is at least $t^*_m + 1$ then just copies it into $L^*_2$ else modifies its release time to $t^*_m + 1$ then copies it into $L^*_2$. By the above definitions and (9), we have

$$OPT(L^*_2) \geq OPT(L^*_2^1) \geq OPT(L^*_2^2).$$

(10)

$$A(L) = A(L_1) + A(L^*_1).$$

(11)

$$OPT(L) = OPT(L^*_1) + OPT(L^*_2).$$

(12)

And by the assumption for $h$ basic chains and Claim 1, we have

$$4A(L^*_2) \geq OPT(L^*_2) \text{ and } 4A(L_1) \geq OPT(L^*_1).$$

(13)

So,

$$4A(L) = 4(A(L_1) + A(L^*_1)) \text{ by (11)}$$

$$\geq OPT(L^*_1) + OPT(L^*_2) \text{ by (13)}$$

$$\geq OPT(L^*_1) + OPT(L^*_2) \text{ by (10)}$$

$$= OPT(L) \text{ by (12)}$$

Hence, this theorem holds. □

References