Replica selection for parallel and multi-wavelength downloading in optical grid networks

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***Abstract*—This paper proposes a replica selection scheme for parallel and multi-wavelength downloading in optical grid networks. In optical grid networks, files replicated at multiple sites are downloaded in parallel to reduce downloading time. Furthermore, each replica is downloaded with multiple wavelengths. Although parallel and multi-wavelength downloading can reduce downloading time, they raise blocking probability of file downloading. To resolve this problem, the proposed scheme selects replicas and establishes lightpaths based on wavelength availability. Through simulation experiments, we show that the proposed scheme efficiently improves blocking probability without increasing average downloading time.**

***Index Terms*—Optical grids, WDM, Parallel downloading, Replica selection.**

I. Introduction

Optical networks have gained tremendous importance due to their large transmission bandwidth using the wavelength division multiplexing (WDM) technology which increases the capacity of a fiber optic link by simultaneously transmitting multiple signals with different wavelengths over a single fiber. In optical networks data is transmitted via a lightpath which is a path assigned a dedicated wavelength. Because the lightpath is established between a client and a server before transmission, transmission bandwidth is guaranteed and thus reliable transmission is realized.

Grid computing integrates geographically distributed computing resources, such as CPUs and storages, through communication networks. A data grid, one of the grid computing techniques, manages distributed data and offers high performance computing [5], [8]. However, data files shared in data grids are generally huge and thus clients take longer to download data files. To enhance the transmission rate, optical grid networks which employ WDM and lightpaths have been proposed [6], [11]. Fig. 1 shows a model of an optical grid network, which connects many sites through an optical network. A single site comprises a master node, storages, and computing resources. The master node schedules jobs and exchanges information such as the amount of free space of data storages. The storages store data files required by jobs and the jobs are executed by computing resources. Note that data files are replicated on storages at multiple sites in order to distribute loads. When a user has a job to execute, the user submits it to a master node of a local site. The job is executed at the local site with data files stored in storages. If the data files required by the job do not exist in the local site, they are downloaded from a remote (other) site. Then the job is executed. We call a local site "client" and a remote site "server" hereafter.

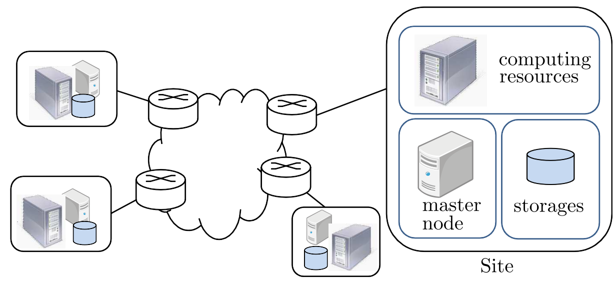

Fig. 1. Optical grid network.

Transmission unit in optical grid networks is larger than that in conventional data grid networks without optical networking. In conventional data grid networks, data is transmitted with electronic packets. On the other hand, in optical grid networks, data is transmitted with lightpaths, which have coarse granularity. Lightpaths cannot be established with the same wavelength in the same link at the same time due to wavelength contention. Furthermore, without wavelength conversion technologies, a lightpath must use a common wavelength in all links along the route (i.e., wavelength continuity constraint), so that file downloading with lightpaths is blocked easier than that with packets. Therefore, wavelength contention is one of the significant issues to be resolved in optical grid networks.

In optical grid networks, files replicated at multiple sites are downloaded in parallel to reduce downloading time [2], [7]. Furthermore, each replica is downloaded with multiple wavelengths (i.e., multiple lightpaths) [10]. Although parallel and multi-wavelength downloading can reduce downloading time, they often generate bottleneck links (i.e., links in which all wavelengths are used) because they simultaneously use more wavelength resources than serial downloading with a single wavelength [7], [19]. As a result, they additionally raise blocking probability of file downloading. To resolve this problem, this paper proposes a replica selection scheme for parallel and multi-wavelength downloading in optical grid networks. The proposed scheme aims to reduce blocking probability of parallel and multi-wavelength downloading by selecting replicas and establishing lightpaths based on wave-

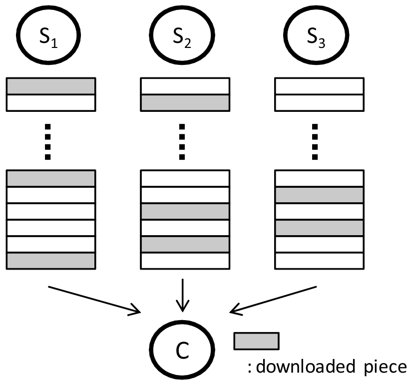

Fig. 2. Parallel downloading (S_i denotes a server and C denotes a client).

length availability. Furthermore, as necessary, the proposed scheme performs multi-path downloading which downloads a replica via multiple edge-disjoint paths between a client and a server in order to distribute loads. The proposed scheme is expected to utilize the wavelength resources efficiently and thus improve blocking probability without increasing average downloading time.

The rest of this paper is organized as follows. In Section II, we discuss parallel and multi-wavelength downloading. Section III describes replica selection. Section IV discusses our proposed scheme. In Section V, the performance of the proposed scheme is discussed with the results of simulation experiments. Finally, we conclude the paper in Section VI.

II. Parallel and multi-wavelength downloading

In data grid networks, including optical grid networks, files are replicated on multiple sites. File replication reduces the bandwidth consumption and helps in load balancing. Replicas are dynamically created and deleted at each site according to replication schemes [1], [4], [14], [17], [18] or caching schemes [9], [13]. In replication schemes, a server decides when and where to create a replica of one of its files as necessary. On the other hand, in caching schemes, when a file is downloaded from a server, a client stores it. If there is no storage space in the client, the storage replaces stored files with the new file.

Parallel downloading is used to reduce downloading time of replicas. As shown in Fig. 2, a file is divided into many small pieces of equal size on servers. A client downloads one of the pieces from each server. When the download of a piece from a server finishes, then the client downloads another piece from the server, and this process continues until the whole file is downloaded. In optical grid networks, replicas are downloaded via lightpaths. A lightpath is established by assigning a wavelength to a route between a client and a server. If parallel downloading is used, lightpaths are established along routes between the client and servers which have selected replicas. Furthermore, multiple lightpaths are established along a route between the client and a server if multiple wavelengths are assigned to the route. Although downloading with parallel and multi-wavelengths reduces downloading time, blocking probability increases with the number of wavelengths (lightpaths) used for each downloading. This is because the increase in the number of wavelengths for each downloading causes the increase in wavelength resource utilization in each link, so that bottleneck links are often generated. Therefore, we should determine the number of lightpaths used for each file downloading carefully.

III. Replica selection

One of techniques to reduce blocking probability of file downloading is replica selection. Replica selection determines which replicas are downloaded based on certain information, e.g., RTT, server loads, and traffic status. By using appropriate replica selection schemes which distribute loads strategically, we expect to suppress bottleneck links. In the past, many replica selection schemes, including schemes which use parallel downloading, have been proposed [3], [12], [15], [16], [19], [20], [21], [23]. However, characteristics of optical grid networks differ from those of conventional data grid networks. In optical grid networks, data files are transmitted via lightpaths. Most replica selection schemes do not consider wavelength resources because they are assumed to work in data grids without optical networking. Thus they are expected not to work well in optical grid networks. Furthermore, when parallel and multi-wavelength downloading is applied to optical grid networks, blocking probability of file downloading increases. We, therefore, need an appropriate replica selection scheme for parallel and multi-wavelength downloading in optical grid networks.

As a replica selection scheme for parallel downloading in optical grid networks, [19] proposed a novel replica (server) selection scheme. In this scheme, replicas are selected while considering network resource availability. This scheme distributes loads for links and suppresses the generation of bottleneck links. As a result, this scheme reduces blocking probability of file downloading. Note that this scheme assumes that a single lightpath is established for a route. On the other hand, as necessary, the proposed scheme establishes multiple lightpaths for a route, and performs multi-path downloading which downloads a replica via multiple edge-disjoint paths between a client and a server in order to distribute loads.

IV. Proposed scheme

A. The idea of the proposed scheme

As shown in Fig. 3, the proposed scheme assumes that one or more replicas are downloaded in parallel and each of those replicas is downloaded with one or more wavelengths (lightpaths). Furthermore, as necessary, the proposed scheme performs multi-path downloading along edge-disjoint paths. Those edge-disjoint paths are prepared as candidates for replica downloading in advance. Specifically, the proposed scheme uses a path-based routing.

Because the proposed scheme uses multi-path downloading, it selects not replicas but combinations of a replica and a lightpath (i.e., a path assigned a wavelength). To efficiently use wavelength resources, the proposed scheme selects the

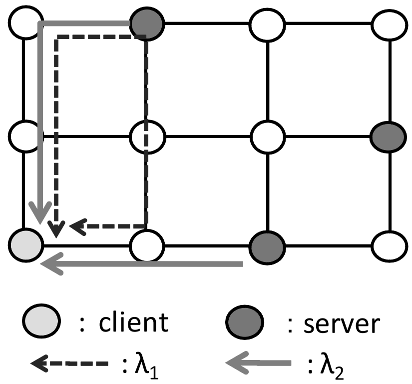

Fig. 3. Proposed scheme.

TABLE I
LIST OF SYMBOLS.

Symbol	Description
$G = (\mathcal{V}, \mathcal{E})$	a directed graph
$\mathcal{S}$	a set of servers which have replicas of a target file
$\mathcal{P}_{i,j}$	a set of edge-disjoint paths from node i to node j
$\mathcal{E}_p$	a set of edges along path p
$\mathcal{U}_e$	a set of used wavelengths in edge e
$\mathcal{R}$	a set of candidate combinations of a replica and a lightpath
$C_{s,p}$	the cost of a path p from a server s
W_e	the number of wavelengths supported by edge e
W	the average number of wavelengths supported by an edge in a network (i.e., $W = \sum_{e \in \mathcal{E}} W_e / \lvert\mathcal{E}\rvert$)
M	the maximum number of lightpaths allowed in a downloading session

combinations based on not only the number of hops but also wavelength availability along paths from servers to a client. In general, replicas are selected based on certain information such as server loads, the number of hops, RTT, traffic status, file size, and wavelength availability. Choice of a set of such information depends on requirements of systems. This paper aims at suppressing the generation of bottleneck links and reducing the blocking probability of file downloading. Lightpaths with long hops wastes wavelength resources, and thus they easily generate bottleneck links. Therefore, we should take into account the number of hops. Furthermore, bottleneck links are generated when all wavelengths in the links are used simultaneously. Thus we expect to efficiently download replicas by considering wavelength availability.

Furthermore, the proposed scheme restricts the number of lightpaths allowed in a downloading session according to a network load in order to efficiently use wavelength resources. Recall that establishing many lightpaths for a downloading session is not efficient in terms of blocking probability. Therefore, the proposed scheme uses fewer lightpaths for downloading when the network load is high. On the other hand, when the network load is low, the proposed schemes tries to establish more lightpaths in order to reduce downloading time. As a measure of the load, the proposed scheme uses wavelength availability on paths. Generally, the numbers of available wavelengths along paths tend to be small when the load is high. In contrast, the numbers of available wavelengths along paths tend to be large when the load is low.

B. The procedure of the proposed scheme

When a downloading request by a client arrives, the proposed scheme selects candidate combinations of a replica and a lightpath, using pre-defined paths. Then the lightpaths are established and the client downloads the replicas via the lightpaths. In what follows, we explain the detail procedure of the proposed scheme. Table I shows symbols used in the explanation. In the proposed scheme, we assume that each client knows which servers have target replicas by using a replica catalog which has location information on replicas [5]. We also assume that wavelength conversion is not available at each intermediate node.

1) Construction of pre-defined paths: We assume that each node fills the role of a client and a server hereafter. In advance, for each node $i \in \mathcal{V}$ and $j \in \mathcal{V}$ in a directed graph $G = (\mathcal{V}, \mathcal{E})$, the proposed scheme makes a set $\mathcal{P}_{i,j}$ of edge-disjoint paths from node i to node j, where $\mathcal{V}$ and $\mathcal{E}$ denote sets of nodes and edges, respectively. The proposed scheme establishes lightpaths via those pre-defined edge-disjoint paths. In this paper, we sequentially construct edge-disjoint paths from i to j as follows. At first, we find the shortest path from i to j on G, using Dijkstra's algorithm, and adopt the path as an edge-disjoint path. Then the edges along the path is removed from G. We find the new shortest path on the resulting graph and the path is adopted as a new edge-disjoint path. Until no routes from i to j remains, the procedure is repeated.

2) Replica and lightpath selection: When a client $c \in \mathcal{V}$ tries to download replicas of a target file, the algorithm shown in Fig. 4 is used to select up to M candidate combinations of a replica and a lightpath for the downloading session. The algorithm sequentially selects the combinations, using information on a set $\mathcal{U}_e$ of used wavelengths in edge e along paths from servers with the replicas to the client, which is collected by signaling. Step (a) is an initialization operation. In step (b), we estimate the cost $C_{s,p}$ of a path $p \in \mathcal{P}_{s,c}$ from a server s which has a replica of the target file to the client c as follows:

$$C_{s,p} = \sum_{e \in \mathcal{E}_p} \frac{|\mathcal{U}_e|}{W_e}, \qquad (1)$$

where $|\mathcal{U}_e|$ denotes the number of used wavelengths in edge e. Step (c) selects a combination of a server s^* (i.e., the replica of the target file located at the server s^*) and a path p^*, which have the smallest $C_{s,p}$. Note that the combination which is the same as previously selected one can be selected. If there are two or more combinations with the minimum cost, the proposed scheme selects one randomly. In step (d), even if the number $|\mathcal{R}|$ of elements in $\mathcal{R}$ does not reach the maximum number M of lightpaths allowed in the downloading session, the algorithm stops according to wavelength availability on the selected path. Specifically, when the network load is high, the algorithm tends to stop despite $|\mathcal{R}|$ does not reach M. On the other hand, when the network load is low, $|\mathcal{R}|$ easily reaches

Input A set $\mathcal{S}$ of servers which have replicas of the target file, sets $\mathcal{P}_{s_i,c}$ of edge-disjoint paths from server $s_i \in \mathcal{S}$ ($i = 1, 2, \cdots, |\mathcal{S}|$) to a client c, a set $\mathcal{U}_e$ of used wavelengths in each edge e along each path $p \in \mathcal{P}_{s_i,c}$, and the maximum number M of lightpaths allowed in the downloading session.

Output A set $\mathcal{R}$ of candidate combinations of a replica and a lightpath.

Step (a) Let $\mathcal{R} := \emptyset$.

Step (b) For each path $p \in \mathcal{P}_{s,c}$ from each server $s \in \mathcal{S}$ to the client c, estimate cost $C_{s,p}$ with (1). If there are no reachable paths to the servers, the algorithm stops.

Step (c) Select s and p with the smallest $C_{s,p}$. Let s^* and p^* denote selected s and p, respectively.

Step (d) If $C_{s^*,p^*} > \alpha W(M - |\mathcal{R}|)$ and $|\mathcal{R}| \geq 1$, the algorithm stops, where α ($0 < \alpha \leq 1$) is a parameter. Otherwise, select a wavelength w^* among available wavelengths randomly. Let $l = \{w^*, p^*\}$ denote a selected lightpath.

Step (e) Let $r = \{s^*, l\}$ denote a candidate combination of the replica located at the selected server s^* and the selected lightpath l and $\mathcal{R} := \mathcal{R} \cup \{r\}$. If $|\mathcal{R}| = M$, the algorithm stops.

Step (f) For each edge e along the selected path p^*, update $\mathcal{U}_e$ as follows:

$$\mathcal{U}_e := \mathcal{U}_e \cup \{w^*\}.$$

Then go to step (b).

Fig. 4. Replica and path selection algorithm.

M. In Step (e), the selected combination is added to $\mathcal{R}$. We use a symbol s^* to describe both of the selected replica and the selected server because the server has only one replica for the target file. Step (f) updates information on wavelength availability.

After selecting a set $\mathcal{R}$ of candidate combinations of a replica and a lightpath, the client sends downloading requests to servers which have selected replicas and then the servers try to establish corresponding lightpaths to the client. Selected replicas are downloaded via those established lightpaths. If multiple lightpaths are established along a path to a server, the replica located at the server is downloaded with those lightpaths (i.e., multiple wavelengths).

V. Performance evaluation

A. Model

To evaluate performance of the proposed scheme, we conduct simulation experiments with a network model shown in Fig. 5. It consists of 24 nodes and 43 bi-directional links. Each node has a site. To establish lightpaths, we use wavelength routing with backward reservation [22]. We assume that there are no wavelength converters at any nodes. For simplicity, we assume that the propagation delay of each link is equal to 1 [msec], and processing time of signaling at each node is 0.1 [msec]. We also assume that the bandwidth D of each wavelength is equal to 10 [Gbps]. The total number W of wavelengths in each link is set to be 32, unless stated otherwise. The number F of different files is set to be 24. Every original file is stored at one of sites and the storage size at each site is set to be 10 [Tbyte]. We define ρ as the offered load per wavelength:

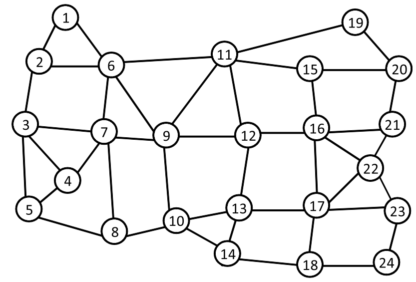

Fig. 5. Network model.

$$\rho = \frac{8 \times \lambda \times L \times 10^3}{D \times W},$$

where λ [1/sec] denotes the average arrival rate of downloading requests and L [Tbyte] denotes the average file size. In order to dynamically create and delete replicas, we use a simple caching scheme which replaces one or more stored replicas with the oldest access time with a new replica, namely LRU, every time the replica is downloaded. We collect 30 independent samples from simulation experiments, and 95% confidence intervals are shown in each figure (even though most of them are invisible). Note that in each figure, α (see Step (d) in Fig. 4) in the proposed scheme is set to be 1.

For the sake of comparison, we use the following four schemes, in which paths are pre-defined like the proposed scheme. In the first scheme, a client selects only one replica located at a server which has the shortest reachable path (in terms of the number of hops), as shown in Fig 6. Note that a reachable path denotes a path along which there are one or more available wavelengths. Then this scheme tries to establish $\min\{A_s, M\}$ lightpaths along the path, where A_s denotes the number of available wavelengths along the path. Specifically, the selected replica is downloaded with M wavelengths when $A_s > M$. When $A_s \leq M$, the replica is downloaded with A_s wavelengths, i.e., all available wavelengths. Wavelengths are selected randomly from among available wavelengths. The second scheme is the same as the first scheme, except that it selects a replica located at a reachable server which has the smallest cost defined by (1). We call the first and second schemes “serial-hop” and “serial-wave” hereafter, respectively.

In the third scheme, as shown in Fig. 7, a client uses parallel downloading with multi-path like the proposed scheme, but a single lightpath is established for each path. This scheme

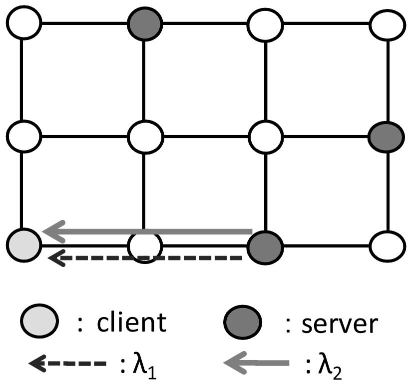

Fig. 6. First and Second schemes.

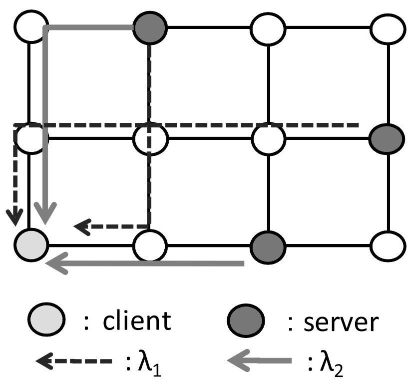

Fig. 7. Third and last schemes.

selects $\min\{A_p, M\}$ different combinations of a replica (a server) and a reachable path in ascending order of the number of hops of the path, where A_p denotes the number of combinations of a replica and a reachable path. Wavelengths are randomly selected without overlap at any edges. The last one uses parallel downloading like the third scheme, but it uses (1) as costs. We call the third and last schemes "parallel-hop" and "parallel-wave", respectively.

B. Performance in a homogeneous model

In this section, we evaluate the performance of the proposed scheme in a homogeneous model. In this model, the size L_f of file f ($f = 1, 2, \cdots, F$) is fixed to 2 [Tbyte]. We assume that user requests of job execution at each site are generated according to a Poisson process with rate λ, and a target file is independently chosen equally likely among all possible files except original files stored at the site.

Fig. 8 shows the blocking probability of file downloading as a function of the offered load ρ, where $M = 4$. Note that the blocking probability BP of file downloading is defined as

$$\text{BP} = \frac{\text{\# of blocked file download attempts}}{\text{total \# of file download attempts}}.$$

File downloading is blocked when there are no paths which have available wavelengths. As we can see from Fig. 8, the blocking probabilities of "parallel-hop" and "parallel-wave" are high because they tend to establish lightpaths with long

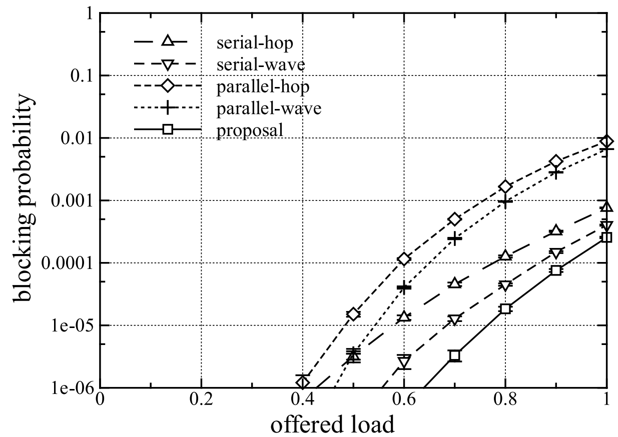

Fig. 8. Blocking probability ($M = 4$).

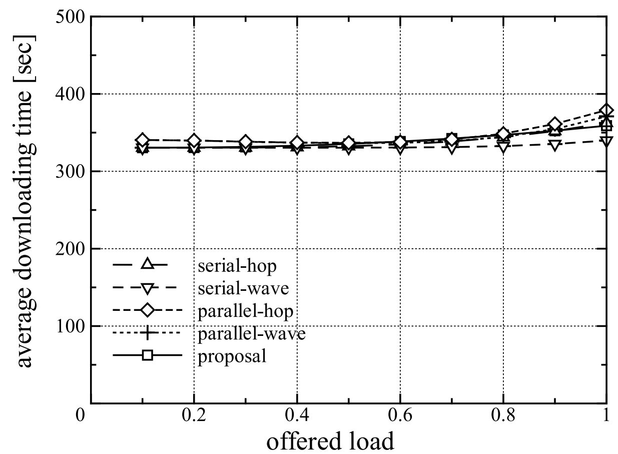

Fig. 9. Average downloading time ($M = 4$).

hops and waste wavelength resources in many links. Furthermore, we observe that the blocking probabilities of "serial-hop" and "serial-wave" is smaller than those of "parallel-hop" and "parallel-wave". This result implies that parallel downloading with a single wavelength is not effective in terms of the blocking probability. We also observe that using (1) as costs reduces the blocking probability efficiently and the proposed scheme shows the excellent performance.

Fig. 9 shows the average downloading time as a function of the offered load ρ, where $M = 4$. Downloading time is the time interval from when a client sends download requests to servers to the time when download of a selected file finishes. We assume that downloading time is 0 when a replica is stored in a local site. As shown in Fig. 9, the average downloading time in all schemes is the almost same.

Figs. 10 and 11 show the blocking probability of file downloading and the average downloading time respectively, as a function of the offered load ρ, where $M = 8$. The proposed scheme efficiently reduces the blocking probability without the increase of the average downloading time, similar to the results with $M = 4$. Note that large M means that the number of lightpaths established for each downloading session

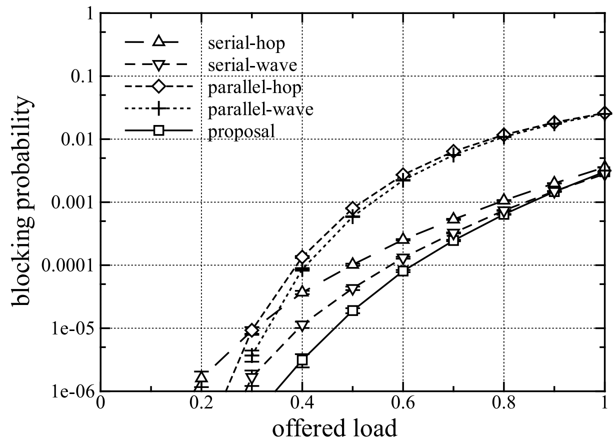

Fig. 10. Blocking probability ($M = 8$).

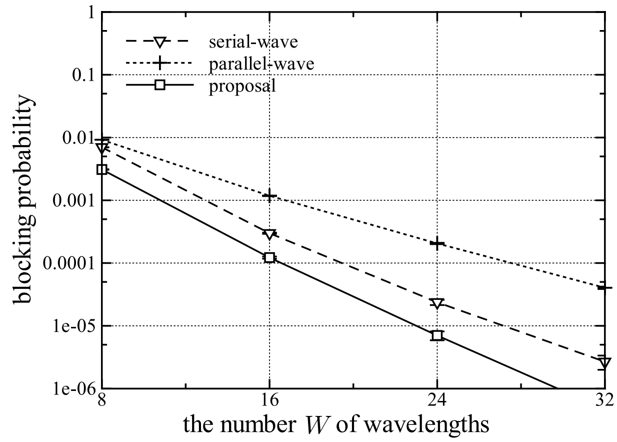

Fig. 12. Blocking probability ($\rho = 0.6$, $M = 4$).

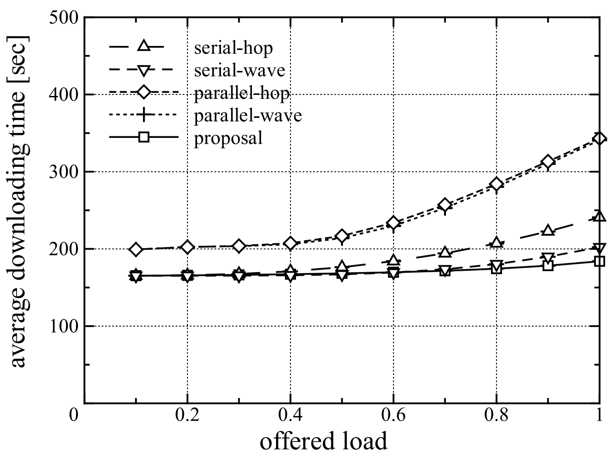

Fig. 11. Average downloading time ($M = 8$).

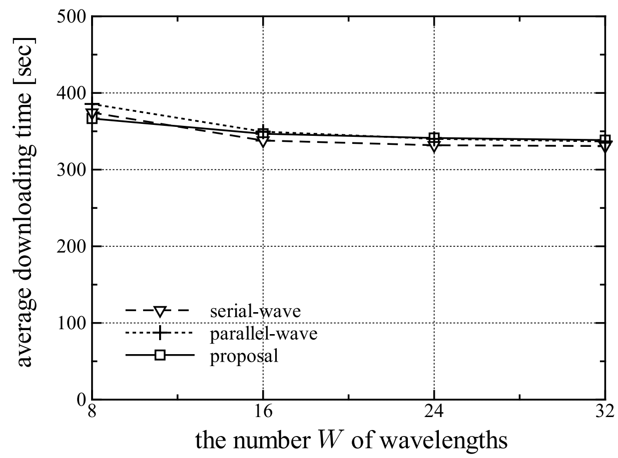

Fig. 13. Average downloading time ($\rho = 0.6$, $M = 4$).

tends to increase. Therefore, the blocking probability of each scheme with $M = 8$ is larger than those with $M = 4$ (see Fig 8). On the other hand, the average downloading time with $M = 8$ is smaller than that with $M = 4$ (see Fig. 9).

Finally, we examine the performance of the proposed scheme against the total number W of wavelengths in each link. Fig. 12 shows the blocking probability of file downloading as a function of W, where $\rho = 0.6$ and $M = 4$. Also, Fig. 13 shows the average downloading time as a function of W, where $\rho = 0.6$ and $M = 4$. As we can see from these figures, the blocking probability of file downloading and average downloading time of each scheme decreases with the increase of W because bottleneck links are hardly generated when W is large. We observe that the proposed scheme reduces the blocking probability more effectively than other schemes. Furthermore, the average downloading time in all schemes is almost the same. We conclude that the proposed scheme efficiently improves the blocking probability without the increase of the average downloading time in this scenario.

C. Performance in a more realistic scenario

We evaluate the performance of our scheme in a more realistic scenario. For this purpose, we assume that user requests of job execution at site n are generated according to a Poisson process with rate λ_n which is proportional to the ratios in Table II. We also assume that a target file is chosen based on weights shown in Table III. Note that the values in these tables are randomly generated. Furthermore, we assume that the size L_f of file f follows an exponential distribution with mean $L = 2$ [Tbyte], where L_f is normalized in such a way that the total file size is equal to $\sum_{f=1}^{F} L_f = 48$.

Fig. 14 shows the blocking probability of file downloading as a function of the offered load ρ, where $M = 4$. Also, Fig. 15 shows the average downloading time as a function of the offered load ρ, where $M = 4$. As we can see from Fig. 14, the proposed scheme efficiently improves the blocking probability of file downloading. Furthermore, from Fig. 15, we observe that the average downloading time in the proposed scheme is slightly larger than that in "serial-wave" when the offered load is high. However, in lightly loaded situations the average downloading time in all schemes is almost the same and the proposed scheme efficiently improves the blocking probability.

Figs. 16 and 17 show the blocking probability of file downloading and the average downloading time respectively,

TABLE II
RATIO OF JOB EXECUTION REQUESTS.

n	1	2	3	4	5	6	7	8	9	10	11	12
ratio	0.065	0.030	0.060	0.061	0.070	0.015	0.026	0.059	0.021	0.043	0.037	0.048
n	13	14	15	16	17	18	19	20	21	22	23	24
ratio	0.028	0.039	0.073	0.070	0.049	0.055	0.011	0.047	0.001	0.019	0.011	0.062

TABLE III
RATIO OF TARGET FILES.

no.	1	2	3	4	5	6	7	8	9	10	11	12
ratio	0.042	0.037	0.018	0.037	0.018	0.032	0.025	0.074	0.064	0.039	0.066	0.022
no.	13	14	15	16	17	18	19	20	21	22	23	24
ratio	0.015	0.076	0.025	0.031	0.047	0.076	0.040	0.052	0.047	0.002	0.064	0.051

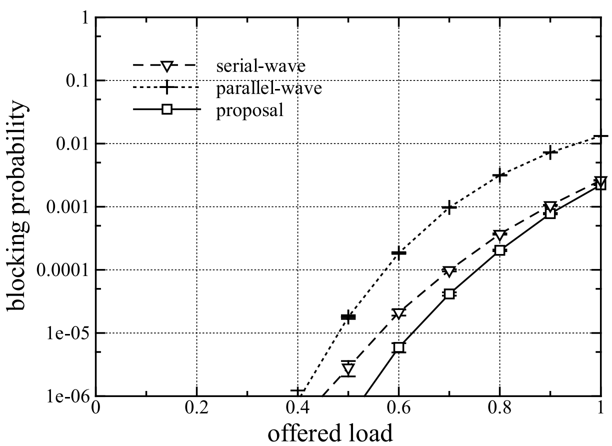

Fig. 14. Blocking probability ($M = 4$).

as a function of the offered load ρ, where $M = 8$. As we can see from these figures, the proposed scheme efficiently reduces the blocking probability without the increase of the average downloading time. Generally, the proposed scheme exhibits the excellent performance in terms of the blocking probability without the increase of the average downloading time in this scenario, similar to the results in the homogeneous model.

VI. CONCLUSION

This paper proposed a replica selection scheme for parallel and multi-wavelength downloading. The proposed scheme aimed to reduce blocking probability of parallel and multi-wavelength downloading by selecting replicas and establishing lightpaths based on wavelength availability. Furthermore, as necessary, the proposed scheme performed multi-path downloading which downloads a replica via multiple edge-disjoint paths between a client and a server in order to distribute loads. Through simulation experiments, we showed that the proposed scheme improves blocking probability without increase of average downloading time.

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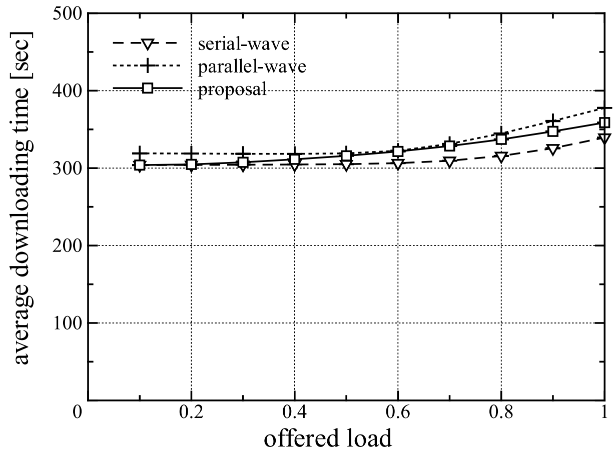

Fig. 15. Average downloading time ($M = 4$).

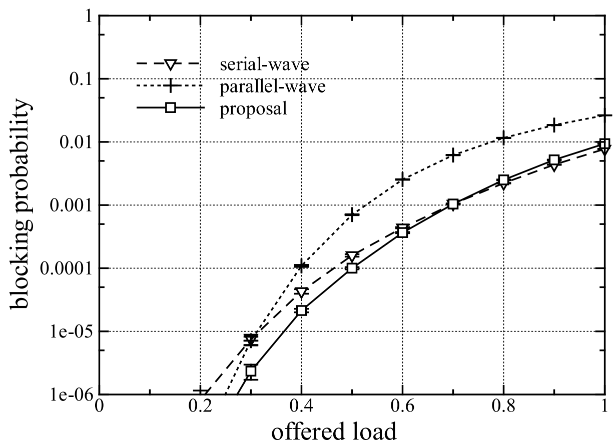

Fig. 16. Blocking probability ($M = 8$).

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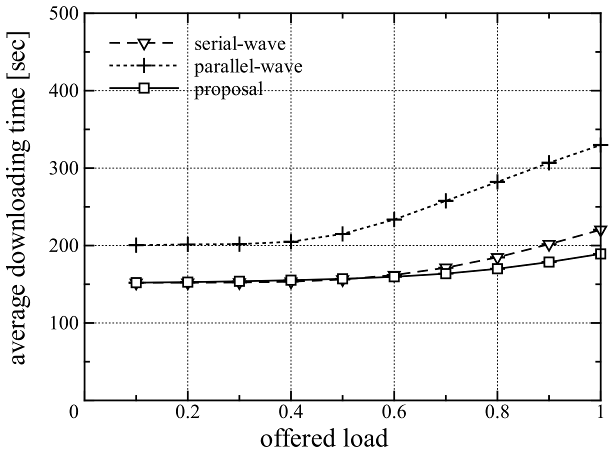

Fig. 17. Average downloading time ($M = 8$).

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