Analytical Blocking Model for Anycast RWA in Optical WDM Networks

Yan Cui and Vinod M. Vokkarane

***Abstract*—In anycast communication, connection requests from a source can be routed to one of multiple candidate destinations, thus helping to improve the overall acceptance of service requests in the network when compared with a traditional unicast. In this paper, we develop a new analytical model to compute the network-wide blocking performance for anycast routing and wavelength assignment (ARWA) in wavelength division multiplexed (WDM) optical networks. Specifically, we calculate the blocking using the reduced-load fixed-point approximation analysis on full wavelength convertible and wavelength continuity constrained optical networks. This model is based on conventional queuing theory for loss systems combined with a conditional probability analysis. Performance results show that our model is accurate and is verified by extensive simulation results.**

***Index Terms*—Analytical model; Anycast; WDM optical networks; Queueing theory; RWA.**

I. Introduction

Optical wavelength division multiplexed (WDM) networks are a promising solution not only for the Internet's increasing bandwidth demands but also for large-scale scientific experimentation generating huge amounts of data. Examples are the European GEANT network [1] and the US Energy Sciences network (ESnet) [2], whose purposes are to enable the transport of data generated by large-scale experiments. These experiments generate huge amounts of data. This data needs to be processed or stored elsewhere and demands very high bandwidth capacity connections. Connection requests in optical WDM networks are commonly provisioned via lightpaths. A lightpath establishment protocol is responsible for finding a route between the source and destination nodes and a wavelength for establishing the connection. Lightpaths are configured using routing and wavelength assignment (RWA).

The connection requests generated by these applications can be classified as either unicast or anycast. Unicast means data transmits from a source node to a destination node, while anycast refers to the transmission of data from a source node to any one member in the candidate destination set. The anycast technique has gained much popularity due to deployment of many significant network services, e.g., content delivery networks (CDNs), data center networks, cloud computing, and video streaming [3–6]. In the mentioned systems, the service request of an individual client can be provisioned by various replica servers or data centers spread geographically over the network. Therefore, the client can be served by any of the available sites.

Given a WDM network structure and the flexible anycast paradigm, researchers focus on the research of the optimization problem of anycast routing and wavelength assignment (ARWA), which involves the selection of a route, wavelength, and a destination for every anycast connection request arriving at the network. References [7–9] have developed different algorithms to solve the ARWA problem, verifying that the anycast communication paradigm can help improve the overall acceptance of connection requests in the WDM network when compared with the traditional unicast. Moreover, for anycast connection requests, because there are multiple candidate destinations and all destinations may be homogeneous or identical, survivability may be provided by establishing routes to multiple destinations. If the server at one destination fails, a different destination can be used by the connection [10,11]. However, these aforementioned papers have not developed the anycast theoretical blocking model.

The anycast paradigm drives new architectural directions for optical WDM networks and poses new network design challenges. Therefore, a model to predict the blocking probability for an anycast paradigm will be useful. Network operators can use such a mechanism to trigger customized policies and reduce blocking of higher priority requests. The analysis of the blocking probability in optical WDM networks was originally developed in [12,13]. The model in [12] took wavelength continuity constraint into account. However, the dynamic nature of traffic was not considered in this model. The author of [13] introduced a model to compute blocking probability on wavelength-routed optical networks using a generalized reduced-load approximation approach considering wavelength continuity constraint. The model is shown to be good for small networks where multilink traffic is not appreciable and is also applicable to mesh networks. Building on the foundations of this work, a model proposed in [14] and a model proposed in [15] use a modified time-reversible Markov chain to account for link correlation and are applicable to arbitrary topologies and traffic patterns. The authors of [16]

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presented an analytical model using the inclusion–exclusion principle of combinatorics with no wavelength conversion and evaluated their model using a first-fit wavelength assignment policy for fixed routing, fixed-alternate routing, and least-loaded routing. In [17], a model was introduced to compute the blocking probability in optical burst-switched networks. However, these authors considered a single-link analysis not the network-wide blocking computation. The authors of [18] also developed a fixed-point approximation algorithm to compute the network approximate blocking probabilities on multiclass WDM networks using a random wavelength assignment policy. More recently, an analytical model was provided in [19] using a reduced-load fixed-point approximation analysis to calculate the network-wide blocking probability considering wavelength conversion and wavelength continuity constraint scenarios.

The majority of blocking models for all-optical WDM networks assume a unicast data transmission scenario and are not suitable for an anycast data transmission scenario. Recently, an analytical model for anycast service was proposed in [20]. The blocking probability was referred to as the distribution of resources over the potential locations and the current state of the lightpaths. However, this model, which used only the information of the current state of lightpaths, is suitable for single link networks. Recently we developed an analytical model in [21] to calculate the network-wide blocking probability for ARWA using reduced-load fixed-point approximation analysis considering a wavelength conversion scenario.

In this paper, we propose a new analytical model to calculate the network-wide blocking probability for ARWA in optical WDM networks; in addition, we formulate the analysis for two common scenarios: (1) full wavelength convertible (FWC) networks and (2) wavelength-continuity constrained (WCC) networks. We assess the results of our model under different sizes of destination sets and numbers of wavelengths and evaluate its correctness against simulation results on ring and mesh network topologies.

The remainder of this paper is organized as follows: Section II introduces the network model assumptions, and we describe the proposed blocking probability analytical model in Section III. Numerical evaluation and model verification are discussed in Section IV, and Section V concludes this paper.

II. Network Model and Assumptions

We assume that a source node is randomly chosen from a node set and a candidate destination set is randomly chosen from the same node set, except the source node for each incoming connection request. For example, this assumption applies in the ESnet and Supercomputer. We consider a stochastic connection request arrival process and model connection arrivals in the network as a Poisson process. We also assume that the holding time of connection requests is exponentially distributed. In the analysis, the total offered load of the network is uniformly distributed among source–destination set pairs.

We use a fixed shortest-hop routing policy to find the optimal route between the source and destination nodes. We denote a route as $r(s, d)$, s is the source node, and d is the destination node. For simplicity, we assume Dijkstra's algorithm is adopted as the routing policy over a non-hierarchical network graph in this paper. For example, as shown in Fig. 1, there are two shortest-hop routes from node n_1 to destination node n_4, i.e., forwarded by intermediate node n_2 and forwarded by the intermediate node n_3, respectively. For the fixed routing policy, we select the route relayed by n_2 as the route for our following derivation. For anycast service, there is a route set from the source to the candidate destination nodes. For each route in a route set, we still use Dijkstra's algorithm to find the optimal route. Additionally, we denote a route set as $r(s, \{d_1, d_2, \ldots, d_m\})$, where s is the source node, and $\{d_1, d_2, \ldots, d_m\}$ is the candidate destination set. For example, as shown in Fig. 1, $r(n_1, \{n_4, n_5, n_6\})$ is a route set that includes routes $r(n_1, n_4)$, $r(n_1, n_5)$, and $r(n_1, n_6)$.

We adopt the first-fit wavelength assignment (FF-WA) policy. In this scheme, all wavelengths are indexed, and the lowest indexed available wavelength is assigned before a higher indexed wavelength.

Also related to the wavelength assignment, we propose two blocking probability models. First, we assume that wavelength conversion between input and output links at all intermediate optical cross connects is available. This allows a connection to set up a lightpath that can make use of a different wavelength at every link along the route. Second, we propose a model for wavelength continuity constrained networks. Under this constraint, the same wavelength must be used on all links along the route used between the source and destination nodes. For instance, as shown in Fig. 1, we assume dashed lines with different colors represent different wavelengths. The fixed route from source node n_1 to destination node n_5 traverses two links: the link from n_1 to n_2 and the link from n_2 to n_5. For FWC networks, the two links can use different wavelengths: for example, red color for the first link and violet for second link. For the WCC networks, the two links along this route must use the same wavelength; only the red color can be chosen for those two links.

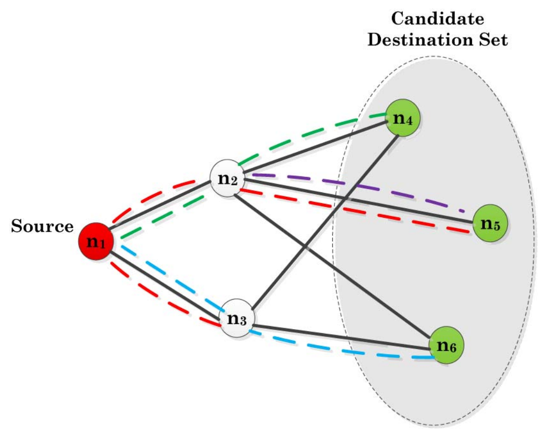

Fig. 1. Anycast network model.

We assume the resource provisioning and allocation for the connection request starts as soon as the call arrives at the network. The connection requests are holding-time-aware, each providing an exact duration.

Anycast service requires selection of a destination from the candidate destinations and a route to that destination. We use a first-fit route selection (FF-RS) policy. In the FF-RS, all routes are numbered. Each route/destination will be checked one by one to verify if there are any available wavelengths for the incoming request. If at least one wavelength is available on each link along a route for FWC networks or at least one same wavelength is available on each link along the route for WCC networks, the reservation is successful. The resources are allocated, and the user/client is positively acknowledged to start transmitting data. Otherwise, the next route will be checked. If there is no available wavelength on any link for all routes included in a route set for FWC networks or if there is not the same wavelength along each link for every route included in a route set for WCC networks, the connection request will be blocked. An example is shown in Fig. 1, which depicts a connection request arrival at the network, with source node n_1 and the candidate destination set $\{n_4, n_5, n_6\}$. The route from n_1 to n_4 will be checked first, followed by the route from n_1 to n_5 and the route from n_1 to n_6. If there is no available wavelength on any link along all three routes for FWC networks or if there is no available same wavelength for any route included in the route set, the anycast connection request is blocked.

III. Analytical Blocking Model

There are three parts in this section. In the first part, we give the computation process of link arrival rates to calculate the link blocking probability, which is the first step in deriving the average network blocking problem. We present our theoretical model on how to calculate the average network blocking probability in the second part. Finally, we adopt a reduced-load Erlang fixed-point approximation algorithm to update network blocking probability after having computed the average network blocking probability without reduced load to get much more accurate network blocking probability. We define an anycast connection request as $R(s, D, \tau)$, wherein s is the source node, D is the destination set, and τ is the holding time of the request. When a connection request arrives at the network, resources need to be provisioned immediately. If the request arrives at the current time and cannot get resource allocation immediately, the request is blocked.

A. Computation of Link Arrival Rate

In order to compute the link blocking probability, we must consider the link arrival rate. Then we follow the procedure in Subsection III.B to compute the average network blocking probability. This section will present how to calculate the link arrival rate.

In the analysis, the total offered load to the network is uniformly distributed among source–candidate destination set pairs. We denote the total mean arrival rate to the network as λ, the arrival rate of a route set between source node s and candidate destination set D as $\lambda^{s,D}$, and the arrival rate of a route between source s and destination d as $\lambda^{s,d}$. In a unicast network, the candidate destination set includes just one destination. We will derive the link j arrival rate λ^j based on unicast networks and anycast networks (unicast is a special case of anycast where $|D| = 1$).

1) Link Arrival Rate for Unicast Networks: In unicast networks, the candidate destination set includes just one destination. We represent a WDM network as a graph $G = (V, E)$, where V is the set of nodes, and E is the set of links. Because a node may be a source node or a candidate destination node, we can find that the total number of combinations of source–candidate destination pairs is $v \cdot (v - 1)$, if the network has v nodes. Because the total offered load to the network is uniformly distributed among source–candidate destination set pairs, we can derive the arrival rate between a source and a destination as

$$\lambda^{s,D} = \lambda^{s,d} = \frac{\lambda}{v(v-1)}. \tag{1}$$

We obtain the arrival rate λ^j for link j by combining the contributions of requests from all routes $r(s,d)$ that traverse such a link. Hence,

$$\lambda^j = \sum_{s,d|j \in r(s,d)} \lambda^{s,d}. \tag{2}$$

2) Link Arrival Rate for Anycast Networks $|D| = 2$: Each source–candidate destination set pair includes a source node and two destination nodes, which means the size of the route set is 2. As each node in an anycast network may be a source node or a destination node, if a network graph includes v nodes, the number of combinations of source–candidate destination set pairs is $v(v-1)(v-2)$. Because the total offered load to the network is uniformly distributed among source–candidate destination set pairs, we can derive the arrival rate of a route set between a source and candidate destination set as

$$\lambda^{s,D} = \frac{\lambda}{v \cdot (v-1)(v-2)}. \tag{3}$$

The request to the route set will arrive at the first route and attempt resource allocation, so the arrival rate of the first route is the same as the arrival rate of the route set. However, if the request coming to the route set is blocked on the first route, the request then arrives at the second route and tries to receive resource allocation. So the contributed arrival rate to the second route is from the requests, which are already blocked on the first route.

In summary, we can derive the arrival rate of each source–destination pair by combining the contributions

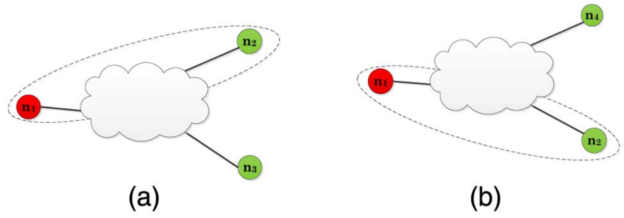

Fig. 2. (a) Route set $r(n_1, \{n_2, n_3\})$ with route $r(n_1, n_2)$ as the first route. (b) $r(n_1, \{n_4, n_2\})$ with route $r(n_1, n_2)$ as the second route.

of requests that arrive at the route set, which include route $r(s, d)$ as

$$\lambda^{s,d} = \sum_{s,D} \lambda^{s,D} + \sum_{s,D} \lambda^{s,D} P^{sd^1}. \tag{4}$$

In the above equation, P^{sd^1} represents the blocking probability of route $r(s, d^1)$, and the first term of the plus is the sum of the arrival rate of source–candidate destination set pairs in which the route $r(s, d)$ is the first route in a route set. The second term is the sum of the arrival rate of route sets in which the route $r(s, d)$ is the second route. We assume $r(s, d^1)$ is the first route of the route set containing $r(s, d)$ as the second route. For example, if we would like to calculate the arrival rate of route $r(n_1, n_2)$, we need to sum all requests traversing this route. Route $r(n_1, n_2)$ is the first route in the route set $r(n_1, \{n_2, n_3\})$ in Fig. 2(a); we need to add the arrival rate of this route set to calculate the arrival rate of route $r(n_1, n_2)$ because all requests to the route set must arrive at the first route and attempt resource allocation. Route $r(n_1, n_2)$ is the second route in the route set $r(n_1, \{n_4, n_2\})$ in Fig. 2(b). When the incoming request to the route set is blocked on the first route $r(n_1, n_4)$, it will try the second route $r(n_1, n_2)$. We need to add the arrival rate of route set $r(n_1, \{n_4, n_2\})$ conditioned on the block happening on the first route $r(n_1, n_4)$ to calculate the arrival rate of route $r(n_1, n_2)$. Considering that the route $r(s, d^1)$ blocking probability P^{sd^1} has already been computed in a unicast network, we can compute the arrival rate of a source–candidate destination pair using the above equation. We can use Eq. (2) to calculate the link arrival rate after having computed the route arrival rate.

3) Link Arrival Rate for Anycast Networks $|D| = n$: We can derive the arrival rate between a source–candidate destination set as

$$\lambda^{s,D} = \frac{\lambda}{v \cdot (v-1)(v-2) \cdots (v-n)}. \tag{5}$$

We can derive the arrival rate of each source–destination pair as

$$\lambda^{s,d} = \sum_{s,D} \lambda^{s,D} + \sum_{s,D} \lambda^{s,D} P^{sD^1} + \sum_{s,D} \lambda^{s,D} P^{sD^2} + \cdots + \sum_{s,D} \lambda^{s,D} P^{sD^{(n-1)}}. \tag{6}$$

This arrival rate of route $r(s, d)$ is equal to the sum of all arrival rates of each source–candidate destination set that includes the route $r(s, d)$ as first route, second route, … $n-1$th route, and nth route. If we assume the probabilities that the first route is blocked, the second two routes are blocked, and the first $n-1$ routes are blocked as P^{sD^1}, P^{sD^2}, and $P^{s,D^{(n-1)}}$, respectively, which have already been calculated for unicast and anycast with two candidate destinations, and anycast with $n-1$ candidate destinations, we can use Eq. (2) to calculate the link arrival rate after having computed the route arrival rate.

B. Network-Wide Blocking Model

The average generalized network blocking model is obtained in three steps. First, we provide a link blocking model based on the Erlang-B model. We then present the route set blocking computation. After having computed route set blocking, we can calculate the average network blocking probability.

1) Link Blocking Analysis: If there is no available wavelength for an incoming request on a link, the request is called blocked on this link. We start by deriving the link blocking analysis. The link blocking computed here will be used later to calculate the route set blocking probability.

We can model a link as a queuing system. We consider the number of wavelengths for each link to be equal and denoted as W and the average holding time of a request is τ. We can calculate the blocking probability of link j, denoted as L^j, which is equal to the Erlang loss formula [13]:

$$L^j = B(W, \lambda^j \tau) = \frac{\frac{(\lambda^j \tau)^W}{w!}}{\sum_{k=0}^{W} \frac{(\lambda^j \tau)^k}{k!}}. \tag{7}$$

In the above equation, λ^j represents the arrival rate of link j.

2) Route Set Blocking Computation Under FWC: As introduced, we assume a fixed routing policy; there is only one route between any source–destination pair for the unicast case, where we denote a route from source node s to destination node d to be $r(s, d)$. But for the anycast case, there is a route set for one source to each member of the candidate destination set.

a) Route set blocking computation for unicast: We can assume that the wavelength allocation on a route is independent between the links that are traversed by this route. Under FWC, different wavelengths can be assigned on different links along a route. As a result, the probability that a connection request gets blocked, which means at least one link along the route has no available wavelength when the connection request arrives at the network, is equal to 1 minus the probability that the connection is not blocked in any of the corresponding links j along the route $r(s, d)$. Hence, we can derive the probability that a route $r(s, d)$ is blocked as

$$P^{s,D} = P^{s,d} = 1 - \prod_{j:j \in r(s,d)} (1 - L^j). \tag{8}$$

b) Route set blocking computation for anycast $|D| = 2$: If the candidate destination set size is two, we assume that the route $r(s,d_1)$ is formed by links $\{j_1, j_2, \ldots, j_{h_1}\}$ and the route $r(s,d_2)$ is formed by links $\{j_1, j_2, \ldots, j_{h_2}\}$. We can classify the links that are traversed by the route set into three sets: one set is CL_{12}, which includes the common links that the two routes both go through, formed by links $\{j_1^{cl_{12}}, j_2^{cl_{12}}, \ldots, j_{h_{cl_{12}}}^{cl_{12}}\}$. Another set is CL_1, which includes the remaining links that are traversed only by $r(s,d_1)$, formed by links $\{j_1^{cl_1}, j_2^{cl_1}, \ldots, j_{h_{cl_1}}^{cl_1}\}$. The third set is CL_2, which includes the remaining links that are traversed by route $r(s,d_2)$, formed by links $\{j_1^{cl_2}, j_2^{cl_2}, \ldots, j_{h_{cl_2}}^{cl_2}\}$. For example, Fig. 3 shows a route set. We can classify the links, which are traversed by the route set into three sets: common link set $CL_{12} = \{j_1^{cl_{12}}, j_2^{cl_{12}}, j_3^{cl_{12}}\}$, remaining links of $r(s,d_1)$ set $CL_1 = \{j_1^{cl_1}, j_2^{cl_1}, j_3^{cl_1}\}$, and remaining links of $r(s,d_2)$ set $CL_2 = \{j_1^{cl_2}, j_2^{cl_2}, j_3^{cl_2}\}$.

If there is no available wavelength on at least one common link, the connection request will be blocked. We can denote this blocking probability as $P_{CL_{12}}$. Given the condition that there is at least one available wavelength on each common link, the connection request will still be blocked if there is no available wavelength on at least one remaining link of route $r(s,d_1)$ and there is no available wavelength on at least one remaining link of route $r(s,d_2)$. We denote the probability that there is no available wavelength on at least one remaining link of route $r(s,d_1)$ and route $r(s,d_2)$ as P_{CL_1} and P_{CL_2}, respectively. Now we can derive the probability that the connection request will be blocked on the route set as

$$P^{S,D} = P_{CL_{12}} + (1 - P_{CL_{12}}) P_{CL_1} P_{CL_2}, \tag{9}$$

wherein

$$P_{CL_{12}} = 1 - \prod_{j \in CL_{12}} (1 - L^j), \tag{10}$$

$$P_{CL_1} = 1 - \prod_{j \in CL_1} (1 - L^j), \tag{11}$$

$$P_{CL_2} = 1 - \prod_{j \in CL_2} (1 - L^j). \tag{12}$$

c) Route set blocking computation for anycast $|D| = 3$: If the candidate destination set size is three, that means a route set includes three routes denoted as $r(s,d_1)$, $r(s,d_2)$, and $r(s,d_3)$. In Fig. 4, route $r(s,d_1)$ is from the s node to d_1, forwarded by intermediate nodes n_1, n_2, n_3, n_5, and n_6;

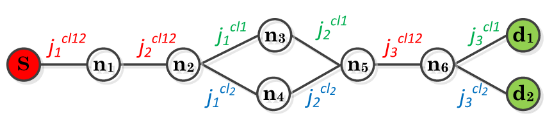

Fig. 3. Route set, $r(s,\{d_1,d_2\})$.

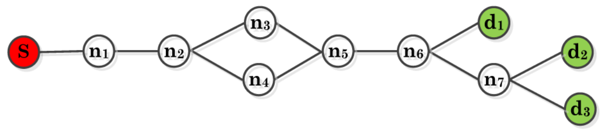

Fig. 4. Route set $r(s,\{d_1,d_2,d_3\})$.

route $r(s,d_2)$ is from the s node to d_2, forwarded by intermediate nodes n_1, n_2, n_3, n_5, n_6, and n_7; and route $r(s,d_3)$ is from the s node to d_3, forwarded by intermediate nodes n_1, n_2, n_4, n_5, n_6, and n_7. We can classify these links traversed by the three routes into the following sets: CL_{123} includes the common links of three routes; CL_{12} consist of the common links of $r(s,d_1)$ and $r(s,d_2)$, which is not traversed by route $r(s,d_3)$; the common links of route $r(s,d_1)$ and route $r(s,d_3)$ compose the CL_{13} set; CL_{23} includes the common links of route $r(s,d_2)$ and route $r(s,d_3)$; the remaining links of route $r(s,d_1)$, route $r(s,d_2)$, and route $r(s,d_3)$ compose sets CL_1, CL_2, and CL_3, respectively. We denote the probabilities that there is no available wavelengths on at least one link of set CL_{123} as $P_{CL_{123}}$, set CL_{12} as $P_{CL_{12}}$, set CL_{13} as $P_{CL_{13}}$, set CL_{23} as $P_{CL_{23}}$, set CL_1 as P_{CL_1}, set CL_2 as P_{CL_2}, and set CL_3 as P_{CL_3}.

We can derive the blocking probability from the following five cases, and each case is mutually exclusive.

Case 1: There is no available wavelength on at least one link of set CL_{123}, which means the common link of the route set happens to have a blocking problem, which leads to the request being dropped on all routes of a route set. We denote the probability of this case as P_1.

Case 2: Given the condition that there is at least one available wavelength on each link of set CL_{123}, there is no available wavelength on at least one link of set CL_{12} and at least one set from the CL_3, CL_{13}, and CL_{23} sets happens to not have an available wavelength on at least one of its links. The request will be dropped on all three routes. We denote the probability of this case as P_2.

Case 3: Given the condition that there is at least one available wavelength on each link of set CL_{123} and on each link of set CL_{12}, there is no available wavelength on at least one link of set CL_{13}, which means the request will be blocked on route $r(s,d_1)$ and route $r(s,d_3)$, and at least one set from CL_2 and CL_{23} happens to not have an available wavelength on at least one of its links, which leads to the request being blocked on route $r(s,d_2)$. Finally, the request will be blocked on all three routes. We denote the probability of this case as P_3.

Case 4: Given the condition that there is at least one available wavelength on each link of set CL_{123}, on each link of set CL_{12}, and on each link of set CL_{13}, there is no available wavelength on at least one link of set CL_{23}, and there is no available wavelength on at least one link of set CL_1. The incoming request will be blocked on all routes. We denote the probability of this case as P_4.

Case 5: Given the condition that there is at least one available wavelength on each link of set CL_{123}, on each link of set CL_{12}, on each link of set CL_{13}, and on each link of set CL_{23}, there is no available wavelength on at least one link of set CL_1, CL_2, and CL_3, respectively. The request will be blocked on all three routes in this case. The probability of this case is denoted as P_5.

In the above, the five cases are mutually exclusive, so we can sum the probability that each case happens to affect the route set blocking probability:

$$P^{S,D} = P_1 + P_2 + P_3 + P_4 + P_5, \tag{13}$$

wherein

$$P_1 = P_{CL_{123}}, \tag{14}$$

$$P_2 = (1 - P_{CL_{123}})P_{CL_{12}}(1 - (1 - P_{CL_{13}})(1 - P_{CL_{23}})(1 - P_{CL_3})), \tag{15}$$

$$P_3 = (1 - P_{CL_{123}})(1 - P_{CL_{12}})P_{CL_{13}}(1 - (1 - P_{CL_{23}})(1 - P_{CL_2})), \tag{16}$$

$$P_4 = (1 - P_{CL_{123}})(1 - P_{CL_{12}})(1 - P_{CL_{13}})P_{CL_{23}}P_{CL_1}, \tag{17}$$

$$P_5 = (1 - P_{CL_{123}})(1 - P_{CL_{12}})(1 - P_{CL_{13}}) \times (1 - P_{CL_{23}})P_{CL_1}P_{CL_2}P_{CL_3}, \tag{18}$$

wherein

$$P_{CL_{123}} = 1 - \prod_{j \in CL_{123}} (1 - L^j), \tag{19}$$

$$P_{CL_{12}} = 1 - \prod_{j \in CL_{12}} (1 - L^j), \tag{20}$$

$$P_{CL_{13}} = 1 - \prod_{j \in CL_{13}} (1 - L^j), \tag{21}$$

$$P_{CL_{23}} = 1 - \prod_{j \in CL_{23}} (1 - L^j), \tag{22}$$

$$P_{CL_1} = 1 - \prod_{j \in CL_1} (1 - L^j), \tag{23}$$

$$P_{CL_2} = 1 - \prod_{j \in CL_2} (1 - L^j), \tag{24}$$

$$P_{CL_3} = 1 - \prod_{j \in CL_3} (1 - L^j). \tag{25}$$

If the candidate destination set size is n, that means a route set includes n routes. Based on the analysis of three destinations for a specific source node, we can conclude the route set blocking problem will include $2^n - n$ cases, which are mutually exclusive. It is difficult to give a generalized equation to calculate the route set blocking probability to include all $2^n - n$ cases.

3) Route Set Blocking Computation Under Wavelength Continuity Constraint: Under the WCC, the lightpath reserved for the connection request must use the same wavelength along the route from the source node to destination node. Due to this constraint, the probability that the connection request gets wavelength allocation successfully is decreased in comparison with that in the FWC network. The constraint can be resolved by considering a conditional probability among the links traversed by the route [13].

First, we define some notations:

Let Y_j be the random variable representing the number of free wavelengths on link j.

Let $q_j(m_j) = \Pr(Y_j = m_j)$ be the probability that exactly m_j wavelengths are available on link j. We assume the random variables Y_j, $j \in r(s,d)$ are independent.

Let Z_R be the random variable representing the number of available common wavelengths on route $r(s,d)$.

Following [15], we assume that, given exactly m_j idle wavelengths on link j, the time until the next call setup on j is exponentially distributed with parameter λ^j. It then follows that the number of idle wavelengths on link j can be thought of as a birth–death process. We then have

$$q_j(m_j) = \frac{W(W-1)\cdots(W-m_j+1)}{\lambda^{j^m}} q_j(0), \tag{26}$$

where

$$q_j(0) = \left[1 + \sum_{m=1}^{W} \frac{W(W-1)\cdots(W-m_j+1)}{\lambda^{j^m}}\right]^{-1}. \tag{27}$$

The probability that n common wavelengths are available on route $r(s,d)$, which consists of the following links $\{j_1, j_2, \ldots, j_{h(r)}\}$, conditioned on the event that every link j_i has exactly m_{j_i} idle wavelength can be defined as

$$p_n(m_{j_1}, m_{j_1}, \ldots, m_{j_{h(r)}}) = \Pr\{Z_R = n | Y_{j_1} = m_{j_1}, Y_{j_2} = m_{j_2}, \ldots, Y_{j_{h(r)}} = m_{j_{h(r)}}\}. \tag{28}$$

For a simple two-link route $r = \{j_1, j_2\}$, we can derive

$$p_n(m_{j_1}, m_{j_2}) = \begin{cases} \dfrac{\binom{m_{j_1}}{n}\binom{W-m_{j_1}}{m_{j_2}-n}}{\binom{W}{m_{j_2}}} & \text{if } n \le m_{j_1}, m_{j_2} \le W, \; m_{j_1} + m_{j_2} - n \le W \\ 0 & \text{otherwise} \end{cases}. \tag{29}$$

In the first part of above equation, the denominator corresponds to the number of combinations that m_{j_2} wavelengths can be selected from W wavelengths on the second link, while the numerator defines the number of combinations of wavelength selection for the second link so that n

wavelengths of selected m_{j_2} wavelengths are also on the first link and $m_{j_2} - n$ wavelengths are not on the first link. For a route of more than two hops, we obtain the following recursive relation:

$$p_n(m_{j_1}, m_{j_2}, \ldots, m_{j_{h(r)}}) = \sum_{k=n}^{k^*} p_n(k, m_{j_{h(r)}}) p_k(m_{j_1}, m_{j_2}, \ldots, m_{j_{h(r)-1}}), \tag{30}$$

wherein $k^* = \min\{m_{j_1}, m_{j_2}, \ldots, m_{j_{h(r)-1}}\}$.

a) Route set blocking computation for unicast: For WCC networks, when a connection request requires the route $r(s, d)$, if there is no idle wavelengths on at least one link along this route, the request will be blocked. Given the event that there is at least one idle wavelength on each link along this route, the connection request will be still blocked if there is no common wavelength on this route. So we can derive the route blocking probability as

$$\begin{aligned} P^{s,d} &= 1 - \Pi_{j;j \in r(s,d)}(1 - L^j) \\ &+ \sum_{m_{j_1}=1}^{W} \cdots \sum_{m_{j_{h(r)}}=1}^{W} q_{j_1}(m_{j_1}) \cdots q_{j_{h(r)}}(m_{j_{h(r)}}) \\ &\cdot p_0(m_{j_1}, m_{j_2}, \ldots, m_{j_{h(r)}}). \end{aligned} \tag{31}$$

b) Route set blocking computation for anycast: If the candidate destination set size is two, there are two routes for each source–destination set pair. The route $r(s, d_1)$ is formed by links $\{j_1, j_2, \ldots, j_{h_1}\}$, and the route $r(s, d_2)$ is formed by links $\{j_1, j_2, \ldots, j_{h_2}\}$. We can classify the links that are traversed by the route set into three sets: one set is CL_{12}, which includes the common link that the two routes both go through, formed by links $\{j_1^{cl_{12}}, j_2^{cl_{12}}, \ldots, j_{h_{cl_{12}}}^{cl_{12}}\}$; another set is CL_1, which includes the remaining links that are traversed by $r(s, d_1)$, formed by links $\{j_1^{cl_1}, j_2^{cl_1}, \ldots, j_{h_{cl_1}}^{cl_1}\}$; the third set is CL_2 and includes the remaining links that are traversed by route $r(s, d_2)$, which is formed by links $\{j_1^{cl_2}, j_2^{cl_2}, \ldots, j_{h_{cl_2}}^{cl_2}\}$. The probability that there is no available wavelength on at least one common link is defined as $P_{CL_{12}}$; the probability that there is no available wavelength on at least one remaining link of route $r(s, d_1)$ is defined as P_{CL_1}; the probability that there is no available wavelength on at least one remaining link of route $r(s, d_2)$ is defined as P_{CL_2}.

For WCC, there are five cases leading to the connection request being blocked on the route set.

Case 1: There is no available wavelength on at least one common link of the route set.

Case 2: There is at least one idle wavelength on each common link, there is no idle wavelength on at least one remaining link of route $r(s, d_1)$, and there is no idle wavelength on at least one remaining link of route $r(s, d_2)$.

Case 3: There is at least one idle wavelength on each common link of the route set, there is at least one idle wavelength on the remaining links of route $r(s, d_1)$, there is no idle wavelength on at least one remaining link of route $r(s, d_2)$, and there is no common idle wavelength for route $r(s, d_1)$.

Case 4: There is at least one idle wavelength on each common link of the route set, there is at least one idle wavelength on the remaining links of route $r(s, d_2)$, there is no idle wavelength on at least one remaining link of route $r(s, d_1)$, and there is no common idle wavelength for route $r(s, d_2)$.

Case 5: There is at least one idle wavelength on each link, which is traversed by the route set. We can divide Case 5 into two subcases given this condition.

Case 5.1: There is no common wavelength on common links. The probability of no common wavelengths on common links is denoted as P_5^1. This case will make the incoming connection blocked.

Case 5.2: There is at least one common wavelength on common links; given this above condition, there is no common wavelength between common links and remaining links of route $r(s, d_1)$, and there is no common wavelength between common links and remaining links of route $r(s, d_2)$. The probability that there is no common wavelength between common links and remaining links of route $r(s, d_1)$ given the condition that there is at least one common wavelength on common links is denoted as $P_5^{2.1}$, and the probability that there is no common wavelength between common links and remaining links of route $r(s, d_2)$ given the condition that there is at least one common wavelength on common links is denoted as $P_5^{2.2}$.

For Case 1, the probability that there is no available wavelength on at least one common link of the route set is equal to 1 minus the probability that each common link of the route set has at least one idle wavelength:

$$P_1 = P_{CL_{12}} = 1 - \prod_{j \in CL_{12}} (1 - L^j). \tag{32}$$

The probability that Case 2 happens is

$$P_2 = (1 - P_{CL_{12}}) P_{CL_1} P_{CL_2}. \tag{33}$$

The probability that Case 3 happens is

$$\begin{aligned} P_3 &= (1 - P_{CL_{12}})(1 - P_{CL_1}) P_{CL_2} \\ &\times \sum_{m_{j_1}=1}^{W} \cdots \sum_{m_{j_{h_1}}=1}^{W} q_{j_1}(m_{j_1}) \cdots q_{j_{h_1}}(m_{j_{h_1}}) \\ &\times p_0(m_{j_1}, m_{j_2}, \ldots, m_{j_{h_1}}). \end{aligned} \tag{34}$$

The probability that Case 4 happens is

$$\begin{aligned} P_4 &= (1 - P_{CL_{12}}) P_{CL_1} (1 - P_{CL_2}) \\ &\times \sum_{m_{j_1}=1}^{W} \cdots \sum_{m_{j_{h_2}}=1}^{W} q_{j_1}(m_{j_1}) \cdots q_{j_{h_2}}(m_{j_{h_2}}) \\ &\times p_0(m_{j_1}, m_{j_2}, \ldots, m_{j_{h_2}}). \end{aligned} \tag{35}$$

The probability that Case 5 happens is

$$P_5 = (1 - P_{CL_{12}})(1 - P_{CL_1})(1 - P_{CL_2})(p_5^1 + p_5^{2.1} \cdot p_5^{2.2}), \quad (36)$$

wherein,

$$P_5^1 = \sum_{m_{j_1}^{cl_2}=1}^{W} \cdots \sum_{m_{j_{h_{cl_{12}}}}^{cl_2}=1}^{W} q_{j_1^{cl_{12}}}(m_{j_1^{cl_{12}}}) \cdots q_{j_{h_{cl_{12}}}^{cl_{12}}}(m_{j_{h_{cl_{12}}}^{cl_{12}}}) \cdot p_0(m_{j_1^{cl_{12}}}, m_{j_2^{cl_{12}}}, \ldots, m_{j_{h_{cl_{12}}}^{cl_{12}}}). \quad (37)$$

$$P_5^{2.1} = \sum_{k=1}^{W} \sum_{m_{j_1}^{cl_1}=1}^{W} \cdots \sum_{m_{j_{h_{cl_1}}}^{cl_1}}^{W} \sum_{m_{j_1}^{cl_{12}}=1}^{W} \cdots \sum_{m_{j_{h_{cl_{12}}}}^{cl_{12}}=1}^{W} \times q_{j_1^{cl_2}}\left(m_{j_1^{cl_{12}}}\right) \cdots q_{j_{h_{cl_{12}}}^{cl_{12}}}\left(m_{j_{h_{cl_{12}}}^{cl_{12}}}\right) p_k\left(m_{j_1^{cl_{12}}}, m_{j_2^{cl_{12}}}, \cdots, m_{m_{j_{h_{cl_{12}}}}^{cl_{12}}}\right) \cdot q_{j_1^{cl_1}}\left(m_{j_1^{cl_1}}\right) \cdots q_{j_{h_{cl_1}}^{cl_1}}\left(m_{j_{h_{cl_1}}^{cl_1}}\right) p_0\left(k, m_{j_1^{cl_1}}, m_{j_2^{cl_1}}, \cdots, m_{j_{h_{cl_1}}^{cl_1}}\right). \quad (38)$$

$$P_5^{2.2} = \sum_{k=1}^{W} \sum_{m_{j_1}^{cl_2}=1}^{W} \cdots \sum_{m_{j_{h_{cl_2}}}^{cl_2}=1}^{W} \sum_{m_{j_1}^{cl_{12}}=1}^{W} \cdots \sum_{m_{j_{h_{cl_{12}}}}^{cl_{12}}=1}^{W} \times q_{j_1^{cl_2}}\left(m_{j_1^{cl_{12}}}\right) \cdots q_{j_{h_{cl_{12}}}^{cl_{12}}}\left(m_{j_{h_{cl_{12}}}^{cl_{12}}}\right) p_k\left(m_{j_1^{cl_{12}}}, m_{j_2^{cl_{12}}}, \cdots, m_{m_{j_{h_{cl_{12}}}}^{cl_{12}}}\right) \cdot q_{j_1^{cl_2}}\left(m_{j_1^{cl_2}}\right) \cdots q_{j_{h_{cl_2}}^{cl_2}}\left(m_{j_{h_{cl_2}}^{cl_2}}\right) p_0\left(k, m_{j_1^{cl_2}}, m_{j_2^{cl_2}}, \cdots, m_{j_{h_{cl_2}}^{cl_2}}\right). \quad (39)$$

We can calculate $P_{CL_{12}}$, P_{CL_1}, and P_{CL_2} using Eqs. (10), (11), and (12), respectively.

In the above, the five cases are mutually exclusive. So we can sum the probability that each case happens to get the route set blocking probability for WCC:

$$P^{S,D} = P_1 + P_2 + P_3 + P_4 + P_5. \quad (40)$$

If the candidate destination set size is three, there are three routes included in one route set. It is very hard to consider all the cases that lead to the route set blocking problem.

4) Average Network Blocking Probability: We can calculate the network-wide blocking probability after having computed every individual route or route set blocking probability, which is simply defined as

$$N = \frac{\sum_{s,D} \lambda^{s,D} \cdot \tau \cdot P^{s,D}}{\sum_{s,D} \lambda^{s,D} \cdot \tau}, \quad (41)$$

wherein $\lambda^{s,D}$ represents the arrival rate of a route set between a source and candidate destination set pair.

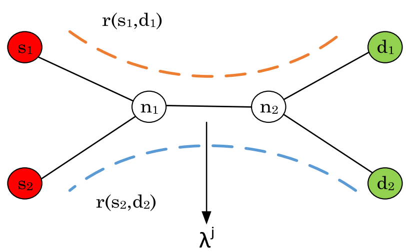

Fig. 5. Reduced-load link approximation.

C. Reduced Load Fixed-Point Approximation for Network-Wide Blocking Probability

Typically, the blocking probabilities and the arrival rate at a link are related because the arrival rate determines the traffic carried by the network, which in turn affects the blocking [13]. We use the reduced-load Erlang fixed-point approximation (EFPA) algorithm [21] to obtain the network blocking probability.

Considering the reduced-load EFPA, the contributed arrival rate into a network link is reduced to make sure that the previous links traversed by the route are not blocking. For instance, let us consider two traffic flows between route $r(s_1, d_1)$ and route $r(s_2, d_2)$, which have one common link on the two routes, as shown in Fig. 5. The common link arrival rate λ^j is equal to the sum of the contributed arrival rates of route $r(s_1, d_1)$ and route $r(s_2, d_2)$, which is itself equal to the arrival rate of the route minus the load blocked on the links traversed before link j. Therefore, for this specific example we have

$$\lambda^j = \lambda^{s_1,d_1} \prod_{l \in r(s_1,d_1): l \neq j} (1 - L^l) + \lambda^{s_2,d_2} \prod_{l \in r(s_2,d_2): l \neq j} (1 - L^l), \quad (42)$$

wherein l is the link that a source–destination pair traverses before traversing link j. Generalizing for any link and source–destination pair, then

$$\lambda^j = \sum_{\substack{r(s,d):\\ j \in r}} \left(\lambda^{s,d} \prod_{\substack{l \in r(s,d):\\ l \neq j}} (1 - L^l) \right). \quad (43)$$

The approximation algorithm shown in Algorithm 1 is not guaranteed to converge. However, in practice, we find that it usually converges within a few iterations, especially for low-medium network loads.

Algorithm 1 Reduced-load Erlang fixed-point approximation

1: Initialize all route set blocking probabilities and all link blocking probabilities to zero, i.e.,
$\hat{P}^{s,D} = 0 \quad \forall\, s, D$ and $L^j = 0 \quad \forall\, j$.
2: Set error threshold ϵ and end $\leftarrow$ **false**.
3: Decompose traffic load to source–destination set pairs based on uniform distribution of traffic load.
4: Decompose and compute the arrival rate to source–destination pairs using Eq. (6).
5: **Repeat**

Decompose and compute the arrival rate to links based on reduced-load due to blocking using Eq. (43).
Compute per link blocking probability L^j, as specified in Subsection III.B using Eq. (7).
For all route set **do**
Compute the route set blocking probability, $P^{s,D}$ under FWC or under WCC.
end for
if $\max^{s,D} |\hat{P}^{s,D} - P^{s,D}| < \epsilon$ **then**
end ← **true**.
else
Update $\hat{P}^{s,D} \leftarrow P^{s,D}$.
end ← **false**
end if
until end **is true**

IV. Numerical Results and Analysis

In this section, we assess the analytical blocking model proposed in Section III and compare its performance with the simulation results. In order to deeply assess the model, we use two different network topologies: a 6-node ring network and the 14-node National Science Foundation network (NSFnet). The topologies are shown in Fig. 6.

In the simulations, we assume a Poisson arrival process with an average arrival rate of λ and an exponential distribution for request holding time with average holding time τ equal to 1. The total offered load is uniformly distributed among source–candidate destination set pairs. For a given simulation set, we change the arrival rate in order to generate the desired offered load ($\rho = \lambda\tau$). The resource provisioning and allocation for a connection request starts as soon as the call arrives into the network. We use the first-fit wavelength assignment and fixed route policy (Dijkstra's shortest path) to determine the route for one source–destination pair and first fit-route selection (FF-RS) policy for anycast requests to do the simulation. We assume eight wavelengths on each link to do the simulation. The simulation results were averaged over 30 seeds of 10^6 connections each. Very narrow 95% confidence intervals were obtained, which have been omitted on the graphs to improve their readability.

The computational complexity of the theoretical model for WCC networks is much higher than that for FWC networks, and the execution times of simulations for WCC networks are close to the execution times of simulations for FWC networks; we compared the execution times (in seconds) between the simulation and analytical model considering the offered loads of 30, 50, and 70 Erlang for unicast ($|D| = 1$) and anycast ($|D| = 2$) in the NSF network with eight wavelengths on each link under two different scenarios: full wavelength conversions and the wavelength continuity constraint. The results in Table I show that the computational complexity of the analytical model is extremely low compared with that of the simulation. For example, the execution time of the theoretical model is up to approximately 200 times faster than that of the simulation at a 30 Erlang load for a unicast FWC network.

We divide the performance analysis into two subsections. First, we analyze the proposed model for the case where the optical WDM network is wavelength-conversion capable. Second, we assess the results for the WCC case. In each subsection, we evaluate the results as a function of the number of candidate destinations for anycast service.

A. Results Analysis of Wavelength Conversion

Figure 7 demonstrates that the analytical procedure with the reduced load EFPA can match the simulation result more accurately compared with the analytical process without adding the reduced load EFPA for both unicast and anycast $|D| = 2$, especially at high offered loads in the six-node ring network. Therefore, we use the theoretical results with reduced load EFPA for the following results analysis.

Figure 8 shows the average network blocking probability performance as a function of the number of candidate destinations for anycast service in a six-node ring network and NSFnet. We can observe that the analytical results accurately match the simulation results. As expected, the blocking probability increases as the offered load increases under the condition that the candidate destination set size is the same. By increasing the number of candidate destinations to a source node, the blocking probability of the network will decrease. This is because increasing the number of candidate destinations means increasing the size of the route set for anycast, providing more opportunities for a request to succeed in resource allocation

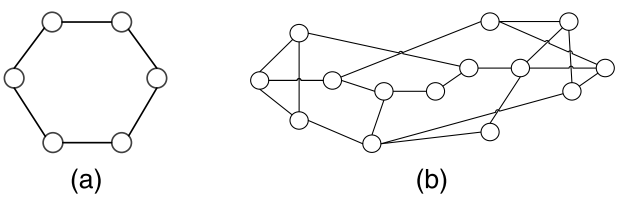

Fig. 6. Network topologies: (a) six-node ring, (b) NSFnet.

TABLE I
Comparison of Execution Time Between Simulation and Analytical Model

		FWC		WCC	
		Simulated	Analytical	Simulated	Analytical
	30	33.31595	0.17550	33.31595	0.23790
1	50	19.98956	0.24375	19.98958	0.35100
	70	14.27828	0.26520	14.27828	0.42120
	30	33.33464	0.46215	33.33464	1.43911
2	50	20.00079	0.55575	20.00079	2.31856
	70	14.28626	0.65910	14.28626	3.12197

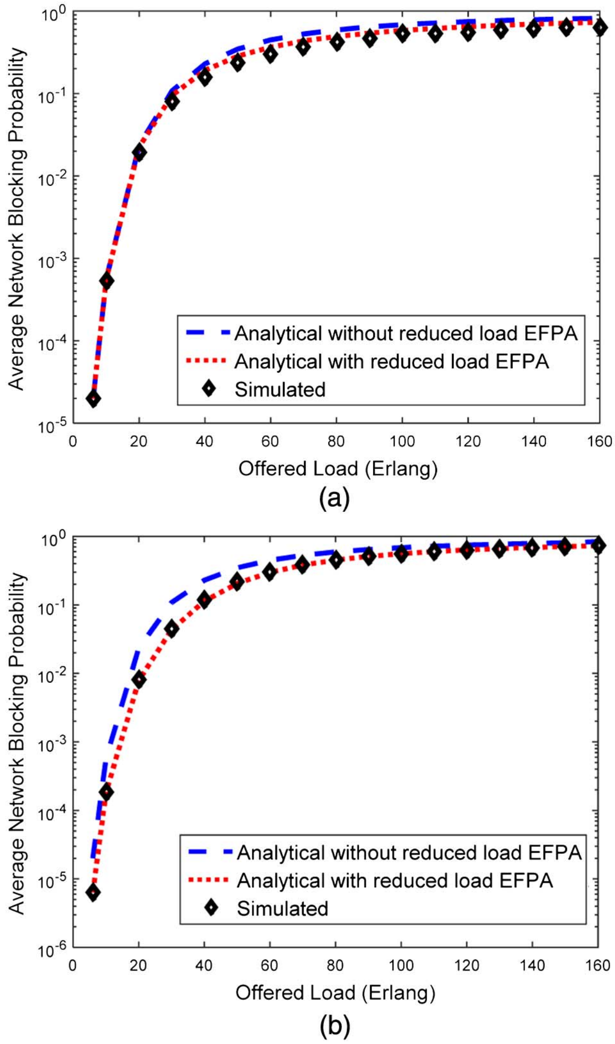

Fig. 7. Network blocking comparison between theoretical result with and without reduced load EFPA and simulation result under FWC networks: (a) unicast, (b) anycast $|D| = 2$ for the six-node ring network.

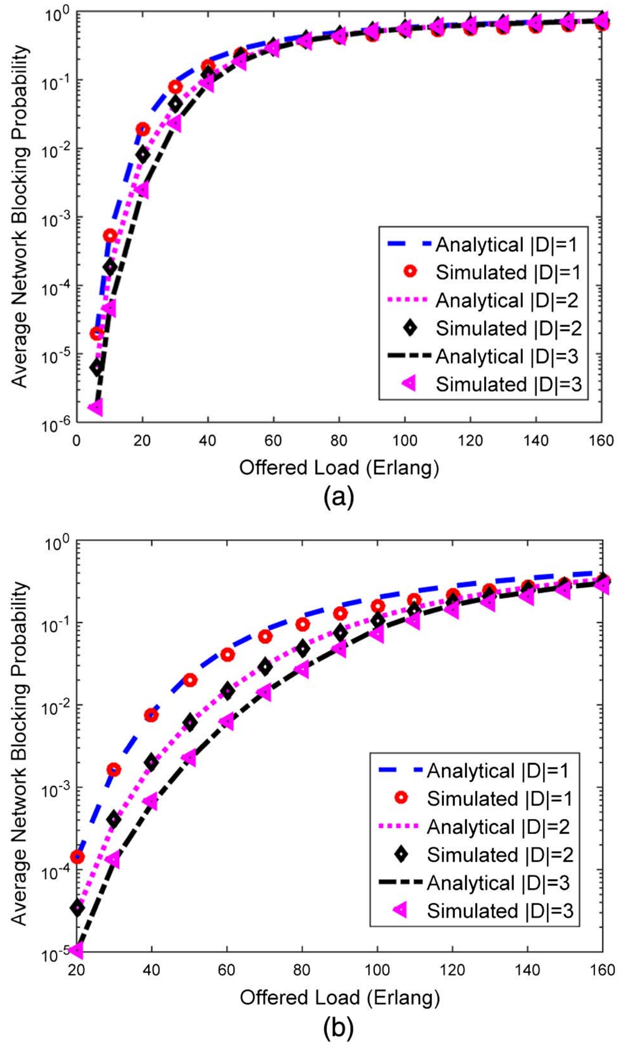

Fig. 8. Network blocking probability under FWC and as a function of the number of candidate destinations: (a) six-node ring network, (b) NSFnet.

based on FF-RS policy. The network blocking probability is decreased down to 1/3 when increasing the number of candidate destinations from one to two and is decreased down to 1/4 when increasing the number of destinations from two to three in the six-node ring network. Additionally, in the NSF network, the network blocking probability is decreased down to 1/4 when increasing the number of candidate destinations from one to two and is decreased down to 1/3 when increasing the number of candidate destinations from two to three at the low offered load.

The above evaluation of results under FWC is based on the assumption of a randomly chosen source node and a randomly chosen destination set in the six-node ring network and NSFnet. The second part of this subsection compares the analytical model and the simulation results for the assumption of a randomly chosen source node, and a destination node is selected among all nodes for NSFnet under FWC. In [22], the best combination of replicas is {2, 6, 9} for three destinations in NSFnet with lower electricity price. We selected {2}, {2, 6}, and {2, 6, 9} as the destination set for a one, two, and three destination set.

Figure 9 shows the average network blocking probability performance as a function of the number of candidate destinations for anycast service in NSFnet. We can observe that the analytical results accurately match the simulation results. The difference is that the blocking probability is a little higher than random assumption with the same conditions.

B. Results Analysis of the Wavelength Continuity Constraint

The second part of the performance analysis compares the analytical model and the simulation results for the

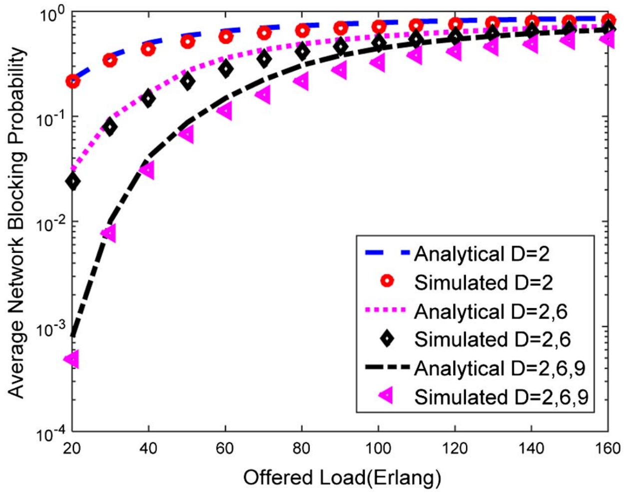

Fig. 9. Network blocking probability under FWC and as a function of the number of candidate destinations in NSFnet.

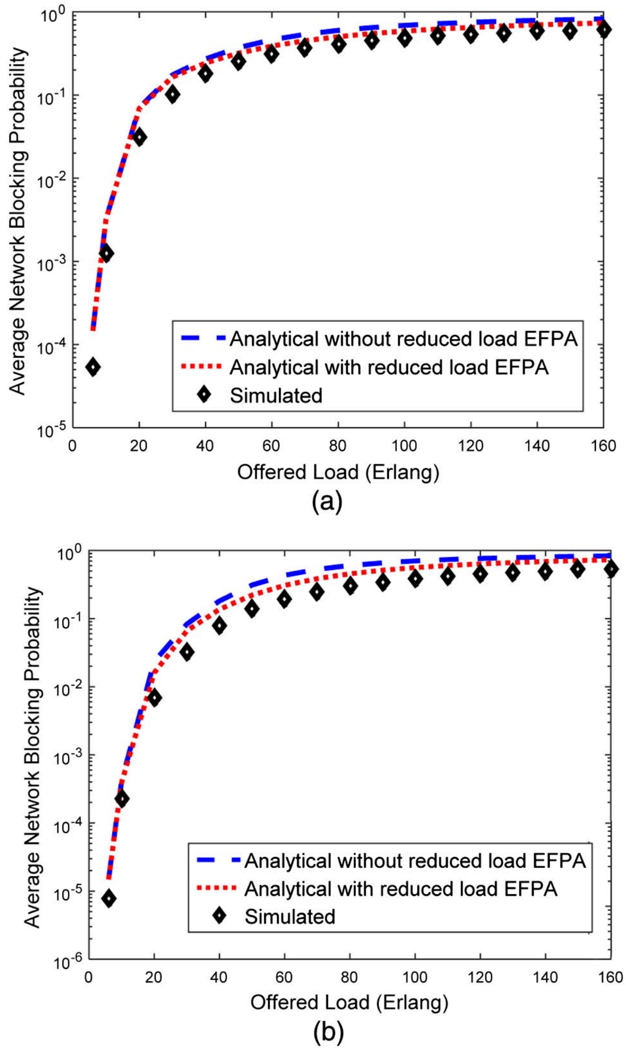

Fig. 10. Network blocking comparison between the theoretical result with and without reduced load EFPA and the simulation result under WCC: (a) unicast, (b) anycast $|D| = 2$ for the six-node ring network.

wavelength-continuity constrained case. Again, we show the results for the six-node ring network and NSFnet topologies.

In Fig. 10, we compare the theoretical result without and with reduced load EFPA with simulation results. As expected, the theoretical result with a reduced load algorithm is much closer to the simulation result compared with the result of an EFPA without reduced load for both unicast and anycast $|D| = 2$ in a six-node ring network.

Figure 11 shows the average network blocking probability performance as a function of the number of candidate destinations for anycast service in a six-node ring network and NSFnet with eight wavelengths available for each link, respectively. We can observe that the comparison between the analytical results and simulation results appears to be quite accurate especially for low and high offered loads for both the six-node ring network and NSFnet topologies. As expected, the blocking probability increases as the offered load increases under the condition that the candidate destination set size is the same. If the offered load is fixed, by increasing the number of candidate destinations to a source node, the blocking probability of the network will decrease. This is because increasing the number of candidate destinations means increasing the size of the route set for anycast, providing more opportunities for a request to succeed in resource allocation based on FF-RS policy because the number of requests is fixed in a one-unit time. The network blocking probability is decreased down to 1/7 when increasing the number of candidate destinations from one to two at the low offered load in the six-node ring network. Additionally, in the NSF network, the network blocking probability is decreased down to 1/5 when increasing the number of candidate destinations from one to two at the low offered load.

We compared the analytical model and simulation result for a fixed destination set with {2} and {2, 6} as the fixed destination set for one and two destinations in NSFnet. Figure 12 shows the average network blocking probability performance as a function of the number of destinations for anycast service in NSFnet. We can observe that the analytical results accurately match the simulation results.

It is worth noting that, comparing the results between the FWC network and the WCC network for the two topologies and the same traffic case, with the same number of wavelengths on each link, the blocking probability on the latter is higher. As we analyzed in Section III, the blocking probability in the WCC case is the sum of the blocking probability contributed from the wavelength conversion blocking and a term that depends on the wavelength-continuity constraint. Also, the analytical model better approximates the FWC network blocking than the WCC network.

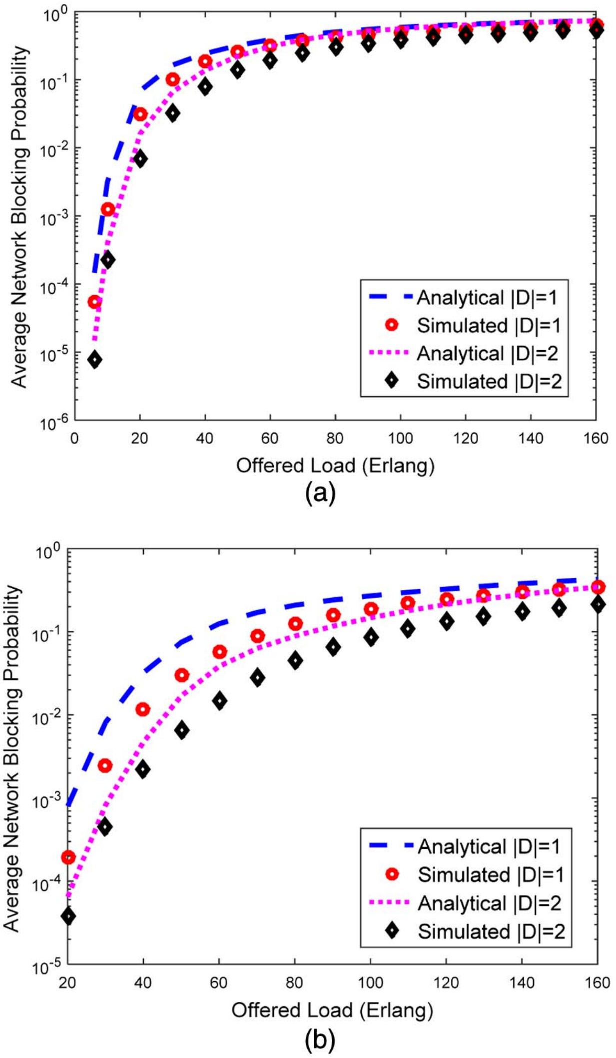

Fig. 11. Average network blocking probability under WCC and as a function of the number of candidate destinations: (a) six-node ring network, (b) NSFnet.

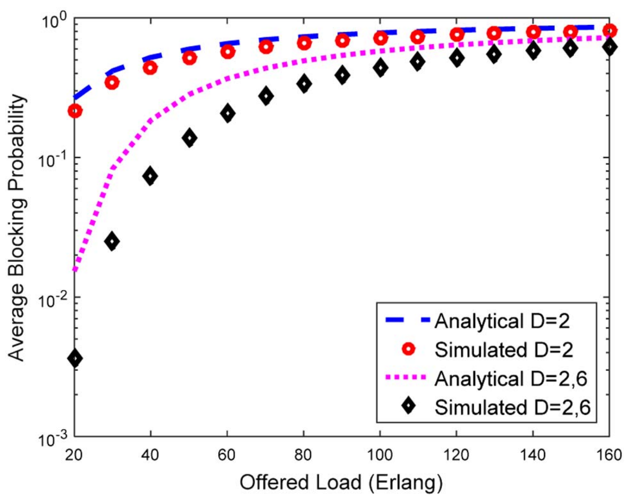

Fig. 12. Average network blocking probability under WCC and as a function of the number of destinations in NSFnet.

V. Conclusion

We present a new analytical model to compute the approximate network-wide blocking probability using a reduced-load EFPA analysis in anycast RWA networks for two common scenarios: FWC networks and WCC networks. The model is based on a conventional Erlang loss model combined with conditional and joint probability. We can predict the FWC networks' blocking probability for one, two, and three candidate destinations for anycast requests. While it is difficult to consider the route dependence to calculate the route set blocking problem for three candidate destinations of an anycast request when modeling the WCC networks, we only modeled one and two candidate destinations for an anycast request under WCC networks. The model can be considered as a useful design tool for anycast RWA networks, as it provides a quantitative methodology for computing how many candidate destinations must be distributed for each source node in order to satisfy some given performance and cost requirements. For future work, we will extend the theoretical models to generalize the anycast paradigm with flexibility in the number of candidate destination nodes for a specific source node using an approximation method.

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