Optimized Parallel Transmission in OTN/WDM Networks to Support High-Speed Ethernet With Multiple Lane Distribution

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***Abstract*—The emerging high-speed Ethernet is expected to take full advantage of the currently deployed optical infrastructure, i.e., optical transport network over wavelength division multiplexing (OTN/WDM) networks. Parallel transmission is a viable option towards this goal, as exemplified by several IEEE and ITU-T standards. The optical virtual concatenation protocol in the OTN layer defined in ITU-T G.709 enables high-speed Ethernet signals to be decoupled into low rate virtual containers. The multiple lane distribution layer defined in IEEE 802.3ba facilitates the optical parallel transmission by stripping Ethernet signals into multiple low rate lanes which can be mapped onto optical channels. In this paper, we propose a new optimization framework for parallel transmission in OTN/WDM networks to support high-speed Ethernet. We formulate the parallel transmission optimization as an integer linear programming problem encompassing three sub-problems: parallel wavelength routing and assignment, usage of electronic buffering for skew compensation, and bufferless parallel transmission. To reduce computational complexity, we deploy multi-objective evolutionary optimization. The numerical results show that parallel transmission in OTN/WDM networks is feasible, and optimal solutions can be obtained with minimum resource consumption and bufferless system design.**

***Index Terms*—Differential delay; High speed Ethernet; Parallel transmission; RWA.**

I. Introduction

Parallel transmission in optical networks is gaining attention due to its potential to support emerging high-speed Ethernet. The main drivers behind this phenomenon can be analyzed from the perspectives of technology and system cost. One critical challenge faced in the adoption of new transport technologies is the need to minimize the impact on the currently deployed infrastructure, which is imposed by the network owners and operators in order to restrain the capital and operational cost [1]. Most present optical networks are designed to support transmission rates of 10 Gbps, or 40 Gbps in some recently deployed networks. While the high-speed Ethernet may scale up to 100 Gbps, parallel transmission over multiple low-speed optical channels is more economical and backward compatible than its high-speed serial counterpart. Moreover, optical reach is known to decrease with the increase of the serial transmission bit rate, due to transmission nonlinear effects, group velocity dispersion, and polarization mode dispersion. Parallel transmission can benefit from using low rate channels to achieve a long optical reach.

Standards have been proposed to facilitate parallel Ethernet transmission over multiple optical channels, such as IEEE 802.3ba, which defines the multiple lane distribution (MLD) layer in Ethernet networks. Here, high-speed Ethernet signals at 40/100 Gbps are distributed into multiple lanes in a round robin fashion, with a data rate compatible with optical channel rates in optical transport networks (OTNs). Initially, four Ethernet lanes were proposed for 40 GE, while 10 Ethernet lanes were used for 100 GE, with each lane running at 10.3125 Gbps [2]. At the same time, the built-in inverse multiplexing protocol in OTN, referred to as optical virtual concatenation (OVC), has been proposed to enable the parallel transmission in optical networks. The OTN architecture specified in ITU-T G.709 defines a hierarchy to transport a variety of client signals over WDM networks, which is backwards compatible with the synchronous optical network/synchronous digital hierarchy (SONET/SDH) standard data rates and is also suitable for the emerging high-speed Ethernet (40/100 Gbps) [3]. An example is shown in Fig. 1(a). Here, the 40 Gbps Ethernet signal is distributed into four Ethernet lanes first, which are then mapped into four ODU-2e containers and routed over four parallel wavelengths. It should be noted that this example shows one-to-one mapping between Ethernet lane (n) and optical channel (m). However, the number of Ethernet lanes and optical channels are not necessarily equal and the corresponding mapping mechanisms are described in IEEE 802.3ba [2].

Parallel transmission in OTN/WDM networks is, however, not without challenges, as it may lead to skew due to the path diversity. Refer to the example shown in Fig. 1(a), and let us assume that four wavelengths are allocated in different fibers and the traffic routed on each wavelength experiences different end-to-end delay. The traffic may not arrive in the destination node in order and needs to be re-sequenced, which is known as the differential delay issue, as illustrated in Fig. 1(b). The Ethernet traffic is stripped into frames which are marked with time order. After transmission over four optical channels, i.e., $\lambda_1, \lambda_2, \lambda_3$, and λ_4, the frame order is $1,3,2,4,\ldots$ (marked in red). To transparently support Ethernet

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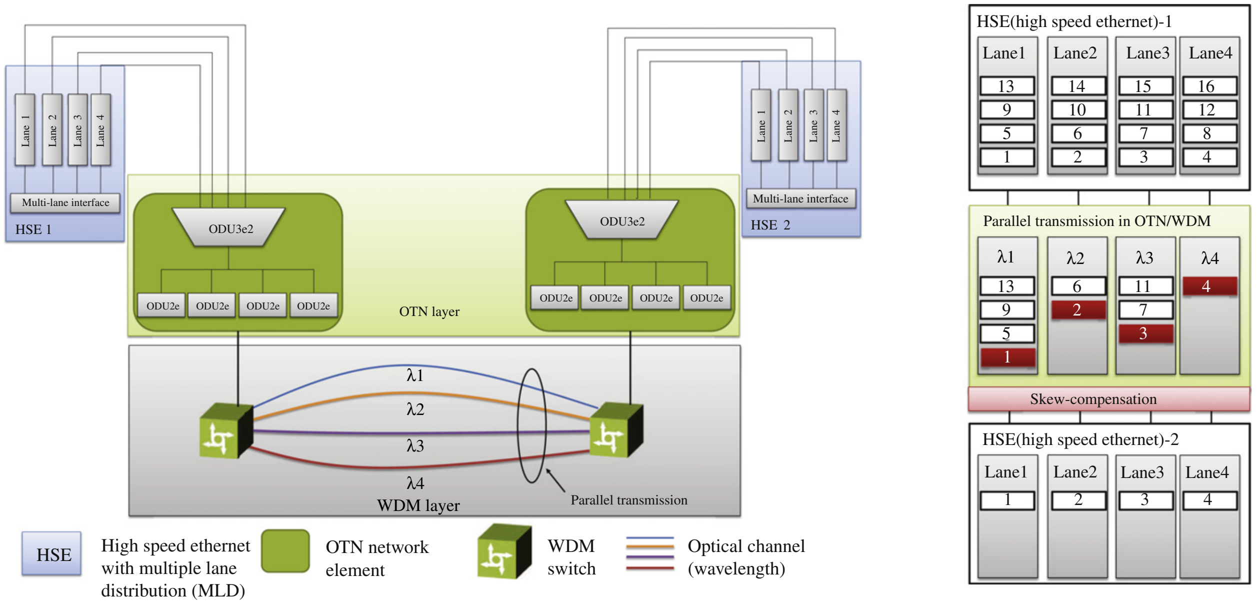

(a) Parallel transmission in an OTN/WDM network to support high-speed ethernet as proposed in IEEE802.3ba [2]

(b) Issues of parallel transmission

Fig. 1. (Color online) Architecture and issues of parallel transmission in OTN/WDM networks to support high-speed Ethernet.

over OTN/WDM networks, the skew should be compensated before traffic enters the Ethernet layer. It is currently open to research whether the parallel transmission in OTN/WDM networks can be implemented without large electronic buffers. Moreover, optimal solutions to parallel transmission are hard to obtain in real-time due to the complexity of the problem.

To address these challenges, in this paper we formulate an integer linear programming (ILP) based optimization model to find optimal parallel paths in an OTN/WDM network, referred to as parallel routing and wavelength assignment (PAR-RWA), and consider two skew compensation mechanisms. The first mechanism allows for the differential delay in the solution, while putting constraints on differential delay within the range of skew compensation capability at the receiver. The second mechanism relies on an optimization scheme which uses scheduling to ensure Ethernet frame ordering without buffering, referred to as *bufferless parallel transmission*. To counter the complexity issue of ILP, we resort to an evolutionary algorithm (EA) based optimization approach to find optimal or near-optimal solutions that meet all the linear constraints defined in the ILP model. The EA is formulated as a multi-objective optimization problem with two objectives, i.e., (i) minimizing the resources consumed by the connection demand to maximize the network profit, and (ii) minimizing the differential delay to minimize the cost. The numerical results show the effectiveness of our optimization framework for parallel transmission in OTN/WDM networks without wavelength conversion, as well as the feasibility of bufferless parallel transmission.

The rest of the paper is organized as follows. Section II presents the related work and our contribution. Section III provides a general description of the optimization problem of parallel transmission in OTN/WDM networks and the related issues. This section is designed for easier understanding of the ILP model that follows in Section IV. Section V discusses the problem size of ILP optimization and presents the evolutionary optimization approach. Section VI presents the numerical results, and finally Section VII concludes the paper.

II. Related Work

Parallel transmission has been studied in the context of multipath routing and inverse multiplexing in connection-oriented networks. In SONET/SDH networks, virtual concatenation (VCAT) has been used as inverse multiplexing, where logical containers with different line rates are defined to divide an optical channel into multiple smaller virtual circuits. Multipath routing mechanisms with consideration of skew compensation have been proposed [4–7], where ILPs are commonly used to select optimal paths from a set of pre-computed paths. Ahuja *et al.* [4] studied the problem of minimizing the maximum differential delay in Ethernet over SONET networks. Srivastava *et al.* [5,6] modeled the required electronic buffering of multipath routing as the sum of buffers required in each path and proposed an ILP based optimization model for the same. Ou *et al.* [7] applied multipath routing in SONET/SDH networks as a survivable routing approach with the differential delay constraint.

The built-in VCAT feature has inspired studies on parallel transmission in OTN/WDM networks in support of high-speed Ethernet. MLD has been proposed in IEEE 802.3ba, which strips high-speed Ethernet signals into multiple lanes [2]. Mechanisms have also been proposed to facilitate high-speed Ethernet over OTN/WDM networks. Santos *et al.* [1] proposed a linear programming (LP) model for routing 100 Gbps Ethernet signals over multiple optical channel data units (ODUs) in the OTN layer. A heuristic was proposed for wavelength assignment in the WDM layer.

In this paper, we use the term *parallel transmission* as a special case of multipath routing, primarily because we deploy the wavelength continuous paths as end-to-end optical channels to support Ethernet MLD, which has not been studied to date. The term parallel transmission was first used in the so-called Terabit LAN for grid applications [8], where lightpaths are used to connect supercomputers over multiple parallel wavelengths (10 Gbps per wavelength), aggregated to transfer Terabit data in parallel. This work identifies parallelism as a paradigm shifting capability for 4k/8k digital media services, such as digital cinema, because there are physical limitations of serial transmission in bit-rates per lambda. Moreover, the usage of parallel ports, transmission channels, and resources with multi-lambda/fiber network interfaces can be applied to improve the total performance. In [9], the skew compensation in parallel transmission of Terabit data has been discussed.

Our paper is different from the previous body of work, since it is an optimization framework for online path computation with dynamic wavelength routing and assignment, while considering skew compensation with wavelength continuity constraint. Note that parallel transmission with paths that allow for wavelength conversion in any node can be modeled the same as any other circuits such as MPLS paths, Ethernet tunnels, etc., which can be addressed with the multipath mechanism developed in [10]. We propose a new method for bufferless parallel transmission in OTN/WDM networks without requiring buffer for frame re-sequencing. In [11], we presented preliminary work on parallel transmission in optical networks. We proposed an ILP model to find optimal paths without computing paths in advance, and the ILP was computationally expensive and thus often limited to solutions with two fiber-level paths in medium size optical networks. In this paper, we therefore extend the previous model and use an EA based multi-objective optimization algorithm to obtain optimal solutions within a reasonable time.

III. Description of the Optimization Problem

A. Problem Description

The optimization problem studied in this paper is based on the OTN/WDM networks, which consist of OTN and WDM layers. The OTN layer is an electronic layer which processes inverse multiplexing of high-speed Ethernet signals into multiple ODU-k containers. Here, we assume that each link between two optical switches consists of two fibers, each for one direction. Each fiber can carry multiple wavelengths. We also assume that high-speed Ethernet is supported over all-optical channels and that electronic processing only happens at source (s) and destination (d) in upper layers (Ethernet and OTN). In other words, the assumed all-optical network provides wavelength continuous paths, and an optical channel (lightpath) is assigned the same wavelength on all links between the source and destination (s–d) pair.

As previously mentioned, parallel transmission in OTN/WDM networks can be deployed with comparably lower speed optical interfaces to support a high-speed Ethernet. Therefore, we assume that each Ethernet transmitter can use at least one wavelength. The number of wavelengths required for parallel transmission of a single connection depends on the mapping between the OTN and WDM layers, which is determined by the logical containers (ODU-k) and the capacity per wavelength. A case of one-to-one mapping has been illustrated in Fig. 1(a), where four wavelengths (10 Gbps per wavelength) are used to support a 40 Gbps Ethernet. The case of $n \neq m$ can be illustrated in the same architecture. Assume HSE1 and HSE2 are 100 Gbps Ethernet networks and the capacity of a wavelength in the OTN/WDM network is 40 Gbps; then 10 Ethernet lanes running at 10.3125 Gpbs can be mapped into four optical channels, i.e., 4×25 Gbps, as suggested in IEEE 802.3ba. Both cases, i.e., $n = m$ and $n \neq m$, result in a bandwidth requirement in the form of the number of wavelengths, which is used as an input to the proposed parallel transmission optimization model. However, the optimization framework presented in this paper does not globally optimize the network performance with all demands known in advance. Instead, it is an online optimization approach which is invoked for each connection demand, as it is dynamically requested. The optimization yields a solution for the connection demand with a set of optical channels (wavelengths), based on the current network load, consumes minimum network resources in the WDM layer, and presents a minimum differential delay.

In this paper, the parallel transmission optimization in OTN/WDM networks is decomposed into three sub-problems. The first sub-problem is to route multiple optical channels (lightpaths) which are not restricted along single fiber-level paths to assign wavelengths under the wavelength continuity constraint. The second sub-problem is minimizing buffer requirements for skew compensation, i.e., using minimum electronic buffering to ensure the right sequence of data over the OTN/WDM network. Finally, the third sub-optimization problem is to deploy parallel transmission in an OTN/WDM network without any buffering, while ensuring frame ordering.

B. Electronic Buffer Requirement

As previously mentioned, electronic buffering is one of the effective mechanisms for skew compensation in parallel transmission. The buffer size required to align traffic from diverse paths is closely related to the cumulative differential delay in the set of paths used as a solution. Assume a set of optical channels, $\mathscr{L} = \{p_i, i = 1, 2, \ldots, k\}$, are computed for a connection demand R and $\tilde{p}$ is the one with the highest delay in $\mathscr{L}$; then the buffer required to avoid traffic disordering is calculated as in Eq. (1):

$$M_R = \sum_{p_i, i=1,2,\ldots,k} C_i \cdot (d_{\tilde{p}} - d_{p_i}), \tag{1}$$

where C_i is the capacity of path p_i, i.e., the capacity per wavelength in the WDM layer and d_p is the delay of path p. In the example shown in Fig. 1(b), $k = 4$ and $\tilde{p} = \lambda_4$. To ensure the transparency to the Ethernet layer, the required buffer should not be larger than the electronic buffer in the OTN layer and the optimization model minimizes the buffer requirement for each connection demand.

IV. Formulation of the Optimization Model for Parallel Transmission

In this section, we present the formulation of the optimization model for parallel transmission in OTN/WDM networks. The optimization model determines PAR-RWA with consideration of constraints. The following information is assumed to be known in advance: network topology, s–d pair, current network status, and available electronic buffer in each node of the OTN/WDM network.

A. Notation

An OTN/WDM network is represented as $G(V,E)$, where V is the set of nodes and E is the set of links. We assume all links in the network have the same number of wavelengths, denoted as W. The set of available wavelengths on link e is denoted as W_e with $W_e \subseteq W$. A connection demand is denoted as $R(s,d,r)$, where s and d are source and destination nodes, respectively, and r is the bandwidth requirement in the number of wavelengths. The link delay of e is denoted by LD_e and $LD_e \in \mathbb{N}$. Path delay is defined as $pd_p = \sum_{e\in p} LD_e$. Paths that are computed in the optimization procedure are placed in a path set, denoted as P.

The formulation of the optimization model relies on the following variables:

- x_p: Binary variable that denotes if a path $p \in P$ is used in the parallel transmission for the connection demand.
- $x_{p,w}$: Binary variable that denotes if a wavelength $w \in W$ is used in the path $p \in P$.
- $x_{p,e}$: Binary variable that denotes if the edge $e \in E$ is used for the path $p \in P$.
- $o_{p,p'}$: Binary variable that denotes if two paths in the same path set P, i.e., $p \in P$ and $p' \in P$ share at least a link.
- $pd_{p,w}$: Integer variable that denotes the delay of the path instance $p \in P$ and wavelength $w \in W$ (becomes 0 if the wavelength w is not used on path p).
- md: Integer variable which is the floor of the maximal delay in the current solution.
- $x_{p,e,w}$: Binary variable that denotes if a path p uses wavelength w on link e.

Note that a path is defined as $p = (e_1, e_2, \ldots, e_n)$ with $e_i = (*,v), e_{i+1} = (v,*) \in E$, which is a concatenation of optical links. Multiple wavelengths in a link e can be assigned to a path p, i.e., $x_{p,e,w_i} = 1, i \geq 1$. The variable $x_{p,e,w}$ is introduced for the purpose of linearization. For instance, a wavelength on link e that is taken by a path p is indicated by $x_{p,e} = 1$ and $x_{p,w} = 1$. The resource consumption on the link e is calculated as $\sum_{p\in P,w\in W} x_{p,e} \cdot x_{p,w}$, which is nonlinear, which can be replaced by a linear function for the linear optimization, i.e., $\sum_{p\in P,w\in W} x_{p,e,w}$, with $x_{p,e,w} = x_{p,e} \cdot x_{p,w}$. Since $x_{p,e,w}$ is determined by a nonlinear function, we therefore define the following constraints for linearization:

$$x_{p,e} + x_{p,w} - x_{p,e,w} \leq 1, \tag{2}$$

$$x_{p,e} - x_{p,e,w} \geq 0, \tag{3}$$

$$x_{p,w} - x_{p,e,w} \geq 0. \tag{4}$$

B. Objective

1) Resource Consumption Minimization: One of our optimization goals is to minimize the resource consumption of each connection demand by optimized PAR-RWA based on current network status. As a result, the number of connections that an OTN/WDM network can accommodate is maximized. The objective function is defined in Eq. (5). Link delay (LD_e) is used as a weight in the objective function such that the shortest paths are preferred in the optimization.

$$\text{Minimize} \sum_{p\in P, e\in E, w\in W} LD_e \cdot x_{p,e,w}. \tag{5}$$

2) Differential Delay Minimization: To minimize the cost of parallel transmission, we define the differential delay minimization as another objective. The maximum difference among the paths used for parallel transmission is identified and minimized in the optimization. The objective function is defined in Eq. (6):

$$\text{Minimize} \quad \text{Max}_{p\in P, w\in W}\{md - pd_{p,w}\}. \tag{6}$$

C. Parallel Routing and Wavelength Assignment (PAR-RWA)

***Routing constraints*:** Routing constraints are defined to ensure that incoming traffic is equal to outgoing traffic at each node (Eq. (7)), except for source and destination nodes where traffic enters and leaves the OTN/WDM network as defined in Eqs. (8) and (9):

$$\forall p \in P, \tilde{v}, v \in V, v \neq s,d: \sum_{e=(\tilde{v},v)\in E} x_{p,e} = \sum_{e=(v,\tilde{v})\in E} x_{p,e}, \tag{7}$$

$$\forall p \in P, \tilde{v} \in V: \sum_{e=(\tilde{v},d)\in E} x_{p,e} = x_p, \tag{8}$$

$$\forall p \in P, \tilde{v} \in V: \sum_{e=(s,\tilde{v})\in E} x_{p,e} = x_p. \tag{9}$$

The loops on a path are prevented by restricting that a node along a path can only have at most one predecessor and one successor, i.e., the outgoing and incoming flow of any node cannot be larger than 1, as stated in Eqs. (10) and (11):

$$\forall p \in P, \tilde{v}, v \in V: \sum_{e=(v,\tilde{v})\in E} x_{p,e} \leq 1, \tag{10}$$

$$\forall p \in P, \tilde{v}, v \in V: \sum_{e=(\tilde{v},v)\in E} x_{p,e} \leq 1. \tag{11}$$

***Wavelength assignment constraints*:** Constraint (12) determines the value of $x_{p,w}$. It sets $x_{p,w}$ to zero when wavelength w in link e is not available for p, i.e., $w \setminus W_e$. Constraint (13) is defined to identify the shared links of two paths. $o_{p,p'}$ takes a value of 1 if path p and p' shares at least a link. When $x_{p,e}$ and $x_{p',e}$ both take a value of 1, the link e is identified as a shared link by p and p'. On the shared link e, a wavelength can be assigned to a path only once. With the wavelength continuity constraint in the WDM layer, $x_{p,w}$ and $x_{p',w}$ cannot take a value of 1 at the same time when $o_{p,p'} = 1$.

Constraint (14) is defined to avoid the wavelength conflict, and constraint (15) ensures that the wavelength assignment is only implemented when path p is selected for the connection demand.

$$\forall p \in P, e \in E, w \in W \setminus W_e : x_{p,e} + x_{p,w} \leq 1, \tag{12}$$

$$\forall p, p' \in P, p \neq p', e \in E : x_{p,e} + x_{p',e} - o_{p,p'} \leq 1, \tag{13}$$

$$\forall p, p' \in P, p \neq p', w \in W : x_{p,w} + x_{p',w} + o_{p,p'} \leq 2, \tag{14}$$

$$\forall p \in P, w \in W : x_p - x_{p,w} \geq 0. \tag{15}$$

Bandwidth requirement constraint: This constraint is defined to ensure that the number of wavelengths assigned to all the paths for connection demand R should be equal to the bandwidth requirement r, i.e.,

$$\sum_{p \in P, w \in W} x_{p,w} = r. \tag{16}$$

D. Skew Compensation

In our model, we assume that the skew compensation happens at the destination node only. Therefore, the size of the available buffer at the egress node of the OTN/WDM network is considered as a critical constraint. We consider the worst case scenario of the skew compensation in parallel transmission, i.e., traffic from any path except for the longest path with the largest delay needs to be buffered.

Buffer constraints: The buffer required for skew compensation depends on the largest delay in the candidate path set. The value of md needs to be found in order to find the best selection of the paths that can yield a minimum buffer size requirement. The delay of each path is defined in Eq. (17), which is then used to determine the value of md in the current path set in constraint (18). The buffer size required for parallel transmission with multiple paths is calculated as $M_r = C \cdot (md - pd_{p,w})$, which should not exceed the available buffer size at the destination node, denoted as M_D. The buffer size constraint is defined in Eq. (19).

$$\forall p \in P, w \in W : pd_{p,w} = \sum_{e \in E} LD_e \cdot x_{p,e,w}, \tag{17}$$

$$\forall p \in P, w \in W : md \geq pd_{p,w}, \tag{18}$$

$$\forall p \in P, w \in W : M_D \geq M_r, M_r = C \cdot (md - pd_{p,w}). \tag{19}$$

E. Bufferless Parallel Transmission

Buffer requirements for skew compensation might hinder wider deployment of parallel transmission in OTN/WDM networks to support high-speed Ethernet, due to additional cost and complexity of the system design. We now present a solution for parallel transmission without any buffering in OTN/WDM networks, referred to as *bufferless parallel transmission*. In IEEE 802.3ba, it has been proposed that Ethernet traffic is first stripped and distributed into Ethernet lanes in the round robin fashion (Fig. 1(a)). Our bufferless parallel transmission is designed based on this principle with a restriction that the Ethernet traffic is stripped into frames of the same size. (We later show in the results section that the bufferless parallel transmission mechanism is independent of the frame size.) The traffic from the high-speed Ethernet is denoted as a sequence of frames, denoted as $F_1, F_2, \ldots, F_n$. The optimization model yields an optimal solution that contains a set of paths with specific path delay that can maintain traffic in order.

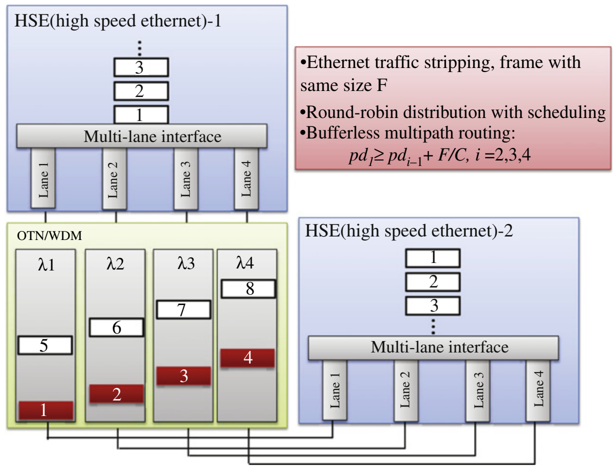

Fig. 2. (Color online) Illustration of bufferless parallel transmission with round robin frame distribution.

Figure 2 illustrates a bufferless solution of parallel transmission for the example from Fig. 1(a). In contrast to the skew compensation, the bufferless parallel transmission mechanism provides multiple paths with a specific time difference to ensure the frames arrive in the right time order. In this example, traffic from HSE1 is distributed over four Ethernet lanes and an Ethernet lane is mapped into an optical channel. Assume that the data rate of one wavelength in the OTN/WDM network is C; then the time for sending a frame into an optical path is F/C. If the delay of path 2 (λ_2) plus the time for sending a frame into path 2 is no less than the delay of path 1 (λ_1), it does not need buffering for traffic on path 1, i.e., $pd_2 + F/C \geq pd_1$. If the differential delay between pd_3 and pd_2 and between pd_4 and pd_3 satisfies the same constraint, no buffer is required for the connection that is transmitted over four lightpaths in parallel.

Bufferless parallel transmission constraint: Let us denote the optical paths in solution set P as p_i, where i is the order of round robin distribution, i.e., if the first frame is distributed into p_i, the second frame will be distributed into p_{i+1}. Based on the discussion on the example shown in Fig. 1(a), we can derive that bufferless parallel transmission can be obtained if the constraint in Eq. (20) is considered, i.e.,

$$\forall p_i \in P, w \in W, v \in V : pd_{p_{i+1},w} \geq pd_{p_i,w} - F/C. \tag{20}$$

There is no restriction that delay p_{i+1} has to be larger than p_i. The constraints defined in PAR-RWA models, such as routing, wavelength assignment, and bandwidth requirement constraints, also hold in the bufferless parallel transmission.

V. Problem Size of the Optimization Model and Evolutionary Optimization

To counter the complexity issue of the ILP optimization we utilize an EA based optimization approach to obtain an optimal or best solution within a reasonable time, fulfilling all the linear constraints in the ILP model. This section analyzes the problem size of the optimization problem for parallel transmission and presents a brief introduction of the evolutionary optimization approach.

A. Problem Size

The complexity of an ILP formulation is known to be exponential in $O(2^n)$, where n is the number of variables. The presented ILP based optimization for parallel transmission has an exponential complexity with n in $O(|P| \cdot (|P| + |E| \cdot |W|))$. This complexity of the ILP prohibits the applicability of the optimization model in practice. For instance, the number of variables $x_{p,e}$ and $x_{p,e,w}$ grow rapidly with the increasing network size. This effect becomes more pronounced with an increase of the number of wavelengths per fiber in the network. Take a simple example: for a network of size $|V| = 15$ and $|W| = 16$, there are $|V| \cdot |V-1| = 210$ node pairs. For each node pair, there are $|P| \cdot |W|$ instances of $x_{p,w}$. Assume four paths are used in the connection, i.e., $|P| = 4$; then we have 13,440 $x_{p,w}$ variables. The number of other variables can be calculated in a similar way. Thus, the total number of variables in the optimization model is very high even for small networks.

The problem size can be reduced by pruning the variables. A common method used in the literature to reduce complexity of optimal multipath routing is to compute a set of paths in advance and use them as input to the ILP models. For instance, if 10 paths are computed in advance and 4 paths are selected as a solution from the optimization, then the number of $x_{p,w}$ variables is reduced to be $C_{10}^{4} \cdot |W| = 3360$. The same reduction can be obtained on the number of other variables. However, the solutions are limited in the pre-computed path set and the complexity of the path computation before optimization should also be considered. With the wavelength continuity constraint, the optimization may fail to yield a feasible solution with a fixed number of paths computed in advance.

EA based optimization has been used to counter the complexity issue of the ILP optimization in the literature, which can obtain an optimal or the best solution in a reasonable time. We therefore resort to an evolutionary optimization approach to solve the presented optimization model for parallel transmission. The details of the evolutionary optimization are presented in the section that follows.

B. Evolutionary Optimization

The evolutionary optimization algorithm is presented in Algorithm 1. It starts with encoding the binary variables from the ILP optimization formulation. In our algorithm, we use the encoding technique proposed in [12] to encode the binary variables into chromosome space and we search for feasible solutions based on the backtracking method. The encoding technique is explained in Appendix A, which is based on [12]. Multi-objective optimization is applied in the evolutionary approach. Therefore, two objective functions defined in Eqs. (5) and (6) are optimized simultaneously to the fullest, i.e., each objective is optimized to the point where any further optimization can lead to a degraded optimality of another objective [12].

Algorithm 1: Evolutionary optimization for parallel transmission

Input: Network $G(V, E, W_e)$; Connection request $R(s, d, r)$; The parallel transmission model

Output: An optimal set of paths for R

Step 1 *Map variables (x_p, $x_{p,w}$, $x_{p,e}$, $o_{p,p'}$, $x_{p,e,w}$) from the optimization model into chromosome space*

1) Decode the binary variables by SAT-decoding [12] into offspring in chromosome space.
2) Generate N offspring in one generation by using the evolutionary algorithm.

Step 2 *Find feasible solutions for each generation*

for *each offspring in one generation* **do**

  1) Use encoded variables as input into a Pseudo Boolean (PB) solver [13]
  2) Find feasible solutions which fulfill all linear constraints.

end

Step 3 *Selection of the solutions with multi-objective optimization*

1) Calculate the objective values defined in Eqs. (5) and (6) of all solutions and evaluate the optimality of the remaining solutions. The linear constraints are used to eliminate the infeasible solutions.
2) Sort the solutions according to the optimality and remove m inferior solutions from the solution space.

Step 4 *Evolution*

1) Generate m new offspring by the evolutionary operations and go back to step 2.

Step 5 *Stop and output an optimal solution after the given number of generations' evolution*

VI. Performance Evaluation

Before evaluating the proposed optimization framework in a realistic scale network, we first evaluate the optimization model in small networks with ILP optimization and the evolutionary optimization. The solutions from both optimization methods are compared with regard to the optimality. The scalability of two optimization approaches is also compared regarding solving the optimization model for parallel transmission in OTN/WDM networks. The comparison between the two optimization approaches utilizes a single objective function defined in Eq. (5). Thereafter, we proceed to evaluate the optimization model in a real-size OTN/WDM network with evolutionary optimization, where two objective functions defined in Eqs. (5) and (6) are used. The multi-objective optimization aims to provide an optimal solution with minimum resource consumption per connection demand while minimizing the differential delay between paths.

All the connection demands arrive in a Poisson process and are uniformly distributed among all node pairs. The number of wavelengths per fiber link is scaled down to 16 in order to reduce the runtime in the simulation. The number of wavelengths required by the connection demands is also scaled down accordingly. The maximum number of wavelengths required by the connection demands is assumed to be five. The minimum bandwidth requirement is assumed to be one wavelength, i.e., at least one wavelength is assigned to support a connection demand between two high-speed Ethernet networks. However, the simulation scenario does not affect the fairness of the comparison and we will show that the ILP optimization fails to yield optimal solutions even with the scaled-down network scenarios. The number of connection demands arriving at the OTN/WDM network is in inverse proportion to their bandwidth requirement, i.e., $1\lambda : 2\lambda : 3\lambda : 4\lambda : 5\lambda = 5:4:3:2:1$. Nevertheless, the simulation scenario in our study aligns with the guidance of the proposals in IEEE 802.3ba TF, which have suggested that both 40 Gbps and 100 Gbps Ethernet can be supported by 4λ, e.g., 4×10 Gbps for 40 Gbps Ethernet and 4×25 Gbps for 100 Gbps Ethernet [2]. The value of $|P|$ implies that the maximum number of diverse routes can be used. For instance, $|P| = 2$ means the optical channels (wavelengths) can be assigned over two fiber-level paths for a connection demand, while all the wavelengths are assigned over the same route with $|P| = 1$.

The *load* A (in Erlang) in our results is defined as $u * h * r/C$, where u is the connection arrival rate and h is the mean connection holding time. r and C represent the average bandwidth requirement and the capacity of one wavelength, respectively. The *bandwidth blocking ratio* is used as a performance metric and is defined as the percentage of the requested bandwidth of blocked connections in the total requested bandwidth. This is due to the fact that different connection demands request different numbers of wavelengths, whereby the resulting blocking has a larger impact on the connection demands with larger bandwidth requirements. On the other hand, fewer connection requests with large bandwidth requirements cause more blocking. The optimization is invoked for 2500 requests at each network load to derive a meaningful average value. The number of evolution generations is set to 150 with 25 individual offspring in each generation, which leads to 3750 evaluations of the objective functions per request. For each results set, the values are averaged over 30 runs. All the results presented in this paper are obtained with the implementation based on the open source optimization framework OPT4J [13,14].

A. Evaluation of Optimality and Scalability

The evaluation of optimality and scalability is based on randomly generated small networks with the number of vertices $|V|$ increasing from 2 to 15. $|E| = 4 \cdot |V| - 6$ links are randomly added into each graph. For each small network, we evaluate three scenarios, i.e., $|P| = 1,2,3$, and all the experiments are performed with the distribution of bandwidth requests as mentioned above. The number of wavelengths per fiber link is 16. The evaluation in this section is performed for the PAR-RWA model with electronic buffering for skew compensation. Both ILP and evolutionary optimization are run 30 times each to derive an average value. For fairness of comparison, the same objective function defined in Eq. (5) is used in both cases, while considering the differential delay issue as a constraint.

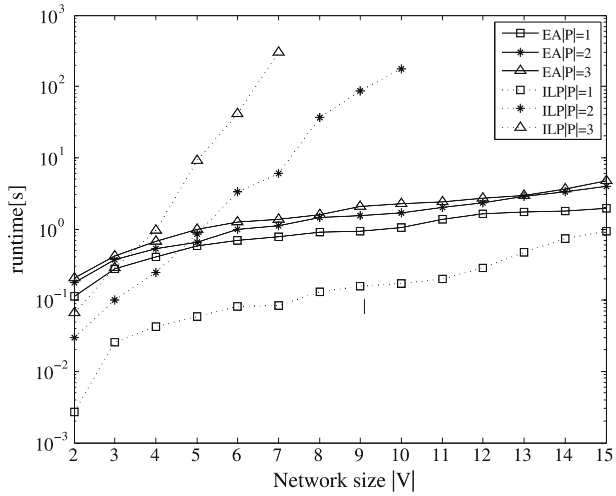

Fig. 3. The scalability comparison.

The first metric used in the evaluation is scalability, which is defined as the average runtime to obtain an optimal solution. The comparison of ILP and evolutionary optimization is shown in Fig. 3 with the y-axis given in logscale. The ILP optimization performs well in finding multiple paths along the same fiber links, i.e., all wavelengths used for parallel transmission are allocated over a single fiber-level path ($|P| = 1$). However, it shows a poor scalability in utilizing diverse fiber links, i.e., $|P| > 1$. The average runtime of ILP optimization increases rapidly with the increase of network size. In addition, ILP optimization can only handle network graphs with at most $|V| = 10$ with $|P| = 2$ and $|V| = 7$ with $|P| = 3$. In contrast, the evolutionary optimization approach shows good scalability by obtaining solutions within a few seconds, regardless of the increasing network size. The scalability study implies that utilizing ILP optimization to obtain optimal solutions for parallel transmission over diverse fiber links in a realistic scale OTN/WDM network can fail due to the complexity issue, either caused by the increasing network size or the number of paths, as discussed in Subsection V.A.

After comparing the scalability, the quality of the solutions from evolutionary optimization is verified by comparing them with those yielded from ILP optimization. The quality of solutions is defined in terms of the normalized hypervolume [15]. The hypervolume of the optimal solution (or best solution) is set to be the baseline of the normalization, i.e., the quality of the optimal solution equals 1. Therefore, the quality of a solution A is defined as *Hypervolume*(A)/*Hypervolume*(*Optimal*/*best*). The results shown in Fig. 4 depict that the evolutionary optimization can yield solutions with the same quality as ILP optimization

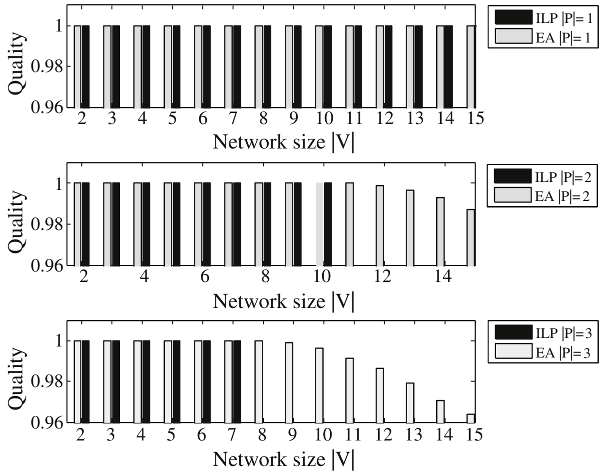

Fig. 4. The quality of solutions comparison.

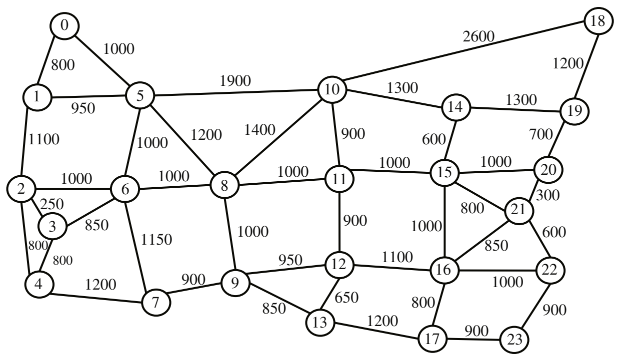

Fig. 5. The USA national network topology.

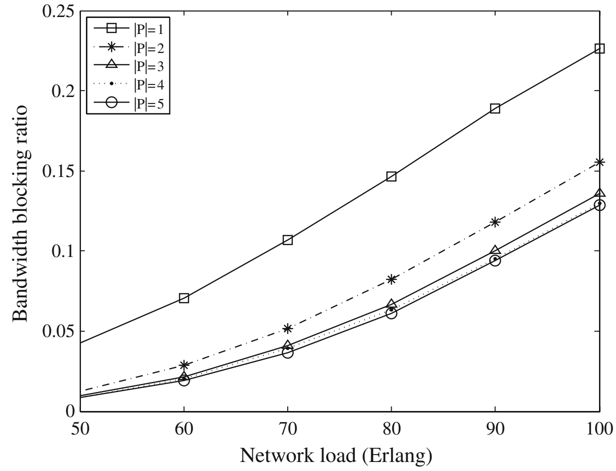

Fig. 6. The impact of $|P|$ on the performance of the bandwidth blocking ratio versus network load.

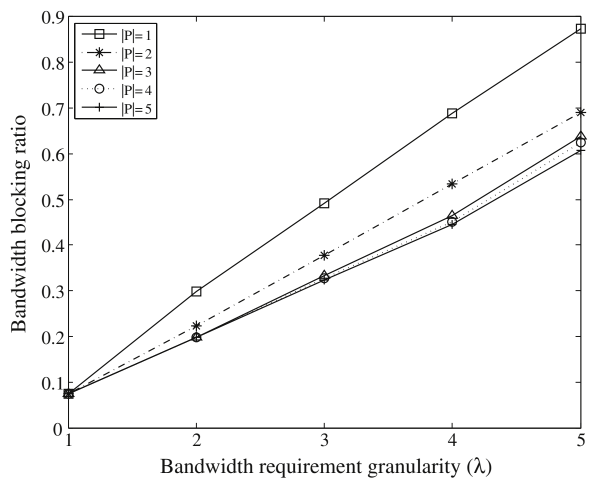

Fig. 7. Bandwidth blocking ratio versus requested bandwidth versus $|P|$: $A = 100$ Erl.

within a reasonable amount of time. When ILP optimization fails to find an optimal solution, the best solution obtained in evolutionary optimization is used as the baseline in normalization. Despite the average quality of solutions decreasing with the increase of network size, evolutionary optimization can find an optimal (best) solution in a reasonable time.

We can conclude from this study that the ILP optimization is restricted by the complexity issue even in small networks. In the rest of this paper, we therefore only use evolutionary optimization to obtain optimal solutions for parallel transmission in a representative USA national network topology (Fig. 5) with link delay denoted in kilometers [16]. The simulation scenario with regard to the number of wavelengths per fiber, request arrival, etc. is the same as described above.

B. Parallel Transmission With Skew Compensation

We evaluate the PAR-RWA model with electronic buffering on the topology shown in Fig. 5. The available electronic buffer at each node is randomly assigned with a value between 5 MB and 10 MB. We perform the evolutionary optimization to obtain an optimal solution that can meet all the constraints defined in Eq. (7) to Eq. (19).

Figure 6 shows the bandwidth blocking ratio with the network load ranging from 50 Erl to 100 Erl. It shows that allowing multiple wavelengths allocated over multiple physical paths, i.e., $|P| > 1$, can decrease the bandwidth blocking ratio. However, spreading traffic over more paths does not necessarily lead to the improvement of network performance regarding the bandwidth blocking ratio. As shown in Fig. 6, $|P| = 4$ and $|P| = 5$ have very similar performance, even though slight improvement has been observed with $|P| = 4$ compared with $|P| = 3$. We further study the relation between the number of paths and the bandwidth requirement and show a set of representative results at a high network load (100 Erl) in Fig. 7. The advantage of parallel transmission over diverse paths in high network load is observed especially with the increasing number of requested wavelengths. However, the same phenomenon has been observed, that is, $|P| = 4$ and $|P| = 5$ do not to improve the performance significantly compared to $|P| = 3$ with regard to the bandwidth blocking ratio. In the remaining numerical results, we will only show the cases with $|P|$ up to 3.

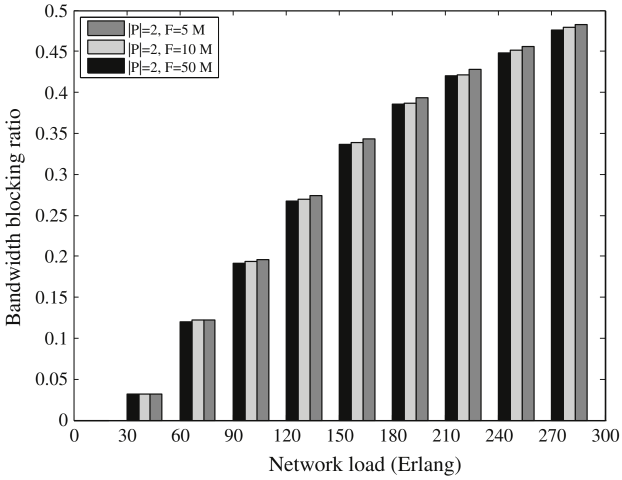

Fig. 8. Frame size versus bandwidth blocking ratio versus network load: $|P| = 2$.

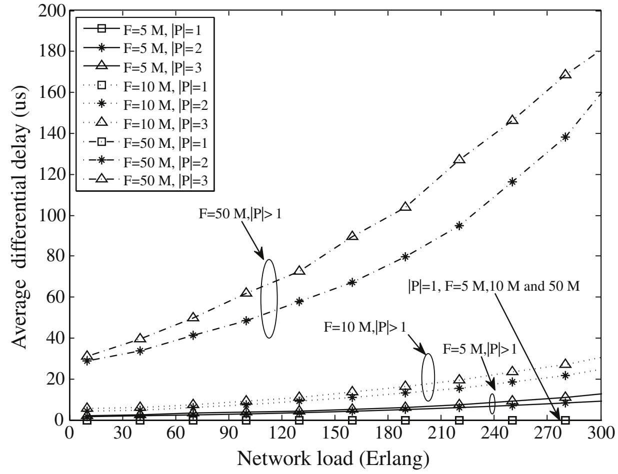

Fig. 9. Average differential delay of bufferless parallel transmission versus network load.

While the parallel transmission over diverse paths in OTN/WDM networks can decrease the bandwidth blocking ratio, it may lead to the cost of electronic buffering. The increasing number of paths used for a single connection leads to an increased differential delay, which opens up a possibility of overflowing the electronic buffer at the destination. We therefore evaluate the resulting differential delay and buffer requirement of the solutions yielded from our optimization model. All the solutions found in this study require a 3.3 MB buffer on average, which is lower than the minimum available buffer size in the network, i.e., 5 MB, and a maximal value of 3000 µs has been observed in all the solutions, requiring a 3.7 MB buffer that is within the available buffer constraints.

C. Bufferless Parallel Transmission

We have shown that the proposed parallel transmission model performs well with skew compensation. We now evaluate the proposed bufferless parallel transmission mechanism. The constraints used in this study are those included in the PAR-RWA model (Eq. (7) to Eq. (16)) and the constraint defined in Eq. (20).

Bandwidth Blocking Ratio: We first study the impact of frame size on the bandwidth blocking ratio. Due to the fact that the same trend has been observed with different $|P|$, we therefore show a set of representative results with $|P| = 2$. The frame sizes used are 5 M, 10 M, and 50 M, and the data rate of an optical channel is assumed to be 10 Gbps. As illustrated in Fig. 8, the frame size that is decided in the Ethernet layer does not affect the bandwidth blocking ratio in the OTN/WDM network. Of note is the performance with a small frame size, i.e., $F = 5$ M here, which has a performance of the bandwidth blocking ratio comparable to that with big frame sizes. This set of results implies that parallel transmission in OTN/WDM networks is feasible even with diverse paths and it is independent of the frame size determined in the Ethernet layer.

Impact of frame size and $|P|$ on differential delay: We also studied the impact of the frame size and the size of $|P|$ on the average differential delay of the solutions from our optimization model for parallel transmission. As shown in Fig. 9, the first observation is that the increasing number of paths used for a connection demand increases the average differential delay. For example, $|P| = 3$ always results in a larger average differential delay compared to $|P| = 2$ with the same frame size. The second observation is that frame size can affect the average differential delay, even though it does not affect the bandwidth blocking ratio. Take $|P| = 2$ as an example: $F = 50$ M results in much higher differential delay in comparison to $F = 10$ M and $F = 5$ M. The difference is as high as 70 µs between $F = 50$ M and $F = 10$ M. While the difference is relatively small between $F = 10$ M and $F = 5$ M, the differential delay of $F = 5$ M is still about 50% less than $F = 10$ M. However, in all cases with different frame size, the average differential delay is lower than 200 µs, which is very small regarding the size of the studied network.

VII. Conclusion

In this paper, we have proposed a novel optimization framework for parallel transmission in OTN/WDM networks to support high-speed Ethernet with MLD. Our approach allows for diverse routing over parallel fiber-level physical paths. The optimization framework included three categories of optimization problems, i.e., PAR-RWA, skew compensation with electronic buffering, as well as a proposal for a bufferless parallel transmission. We formulated the optimization model based on ILP and solved it in a scalable fashion with evolutionary optimization.

The numerical results showed that parallel transmission in OTN/WDM networks is feasible, and optimal solutions can be obtained with minimum OTN/WDM resource consumption and minimum buffer requirement. We made a proposal to apply optimal parallel transmission in OTN/WDM networks without any buffers, which can be achieved by using the proposed bufferless parallel transmission mechanism. The numerical results showed the feasibility of the bufferless transmission, which was independent of the frame size stripped from the Ethernet layer. Overall, our framework is applicable for

TABLE I
AN EXAMPLE OF TWO CHROMOSOME INDIVIDUALS

Variable:	x_p	$x_{p,w}$	$x_{p,e}$	$o_{p,p'}$	$x_{p,e,w}$
Chromosome individual 1					
σ	0	1	0	1	1
ρ	0.5	0.4	0.6	0.7	0.3
Chromosome individual 2					
σ	0	0	0	1	0
ρ	0.7	0.3	0.4	0.3	0.8
Chromosome individual after crossover					
σ	0	1	0	1	0
ρ	0.6	0.4	0.6	0.5	0.6

Ethernet parallel transmission over multiple wavelengths allocated in the same fibers (a single fiber-level path) or diverse fibers (multiple fiber-level paths) in OTN/WDM networks, optimally utilizing available electronic buffers. It is also applicable in OTN/WDM networks where buffers are not available.

APPENDIX A

The encoding technique used in this paper for EA based optimization is based on the approach proposed in [12]. We hereby provide a brief overview; please refer to [12] for further details. Each variable is assigned a priority value $\rho, \rho \in \mathbf{R}^+$ and a binary value $\sigma, \sigma \in 0,1$. The value of σ defines the decision phase of each variable while the value of ρ defines the priority of the variable in the searching process, i.e., the variable with higher priority will be handled first. Two example chromosome individuals are shown in Table I. In the evolutionary optimization presented here, the crossover on the value of σ is a simple selection between individuals while the crossover on the real value ρ is performed by the simulated binary crossover (SBX) [17]. An example individual after crossover is shown in Table I.

Searching in the solution space is based on a backtracking technique which tracks back when the assigned value is not feasible for a variable. Figure 10 illustrates the searching procedure for the chromosome individual 1 defined in Table I. The variable $o_{p,p'}$ is assigned the highest priority with a decision phase defined as 1; therefore, the search starts from $o_{p,p'} = 1$. The searching phase stops when a feasible solution is found.

The evolution through the generations is based on the objective values, and the quality of the solutions improves with the iterative reproduction and selection. The inferior solutions are removed to ensure a convergence towards an optimal value. In each generation, a pseudo-Boolean (PB) solver is used to find the feasible solutions that meet all the linear constraints for each chromosome.

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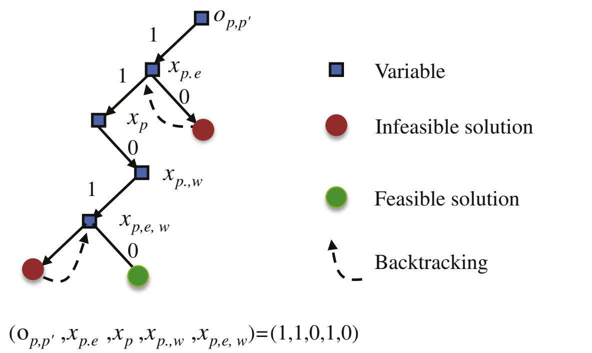

Fig. 10. (Color online) Illustration of backtracking for a feasible solution for chromosome individual 1.

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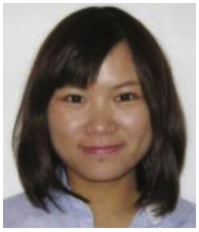

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