On the Usage of FDLs in Optical Parallel Transmission to Support High Speed Ethernet

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***Abstract*—Parallel transmission in the optical layer can enable a scalable network migration from low speed interfaces to high speed serial interfaces, such as 100Gbps Ethernet, as they become available. It is based on the principle of inverse-multiplexing which distributes high speed data stream into multiple low rate optical paths. The main challenge in parallel transmission is the differential delay experienced by different paths. Thus so far, electronic buffering has been widely used to compensate for differential delay. However, at very high speed line rates, such as 40Gbps or even 100Gbps, electronic buffering maybe a challenge. In this paper, we study the usage of Fiber Delay Lines (FDLs) for compensation of differential delay in optical parallel transmission in support of high speed Ethernet services. To this end, we formulate the problem of optimal usage of FDLs in optical networks an Integer Linear Programming (ILP) problem. The results are encouraging as they show that discrete nature of delay provided by FDL buffers is not as limiting as expected, and that FDLs carry potential to enable optical parallel transmission without the need to provide large electronic buffers.**

I. Introduction

Video, data-center and mobile backhaul traffic promises to dominate much of metro traffic in the near future causing speculation for bandwidth exhaustion in the C-band. This has led to motivations for 100 Gbps per wavelength proposals especially in the Ethernet space. One of the major applications of 100Gbps Ethernet (100GbE) technologies is to adapt 100 GbE interfaces in some plausible form for server blades in data centers for both intra-datacenter as well as inter-data center connectivity. A second application is focused on the metro transport space for Optical Transport Network (OTN) type traffic and moving of large data chunks between IP routers with large routing-fabric capacities and 100GbE interfaces. Both applications require transportation of data in the 100-150 km range without 3R regenerator sites. Since the optical technology for provisioning of serial 100Gbps only exists in lab-trials, it has been proposed that multiple MAC layouts ranging from 10x10Gbps, 27.5x4Gbps, 3x40Gbps and so on, making use of WDM spectrum and hence a parallel PHY [1]. The idea is to transport this singular, unified 100 Gigabit Ethernet MAC over such a diverse PHY, till the point of time when 100GbE serial PHY becomes a reality.

Parallel transmission of high speed Ethernet signals over low rate optical channels is also favored by the network carriers due to its backwards compatibility. It can utilize the legacy optical WDM networks where capacity per wavelength is typically 10Gbps, or 40Gbps sometimes. An implementation example is shown in Figure 1, where 100GbE signals are distributed to 10x10G LAN PHY and transmitted on optical wavelengths of 10Gbps via 10G XFPs (10 Gigabit Small Form Factor Pluggable) transceivers. The 10Gbps Ethernet signals can be transmitted over interconnected OC-192 (10Gbps) optical WDM network. However, optical parallel transmission is not without challenges. Despite the ever increasing number of wavelengths per fiber, allocation of multiple wavelengths along a single route is still a challenge, especially in a well utilized network. On the other hand, transmission over diverse fiber links can experience different end-to-end delays, leading to frame disordering at the receiver side, referred to as differential delay issue. Electronic buffers are commonly used to counter this issue, as they can cache the frames in the process of ordering. However, the latter process does not scale well at Gbps speeds and may even become overly expensive.

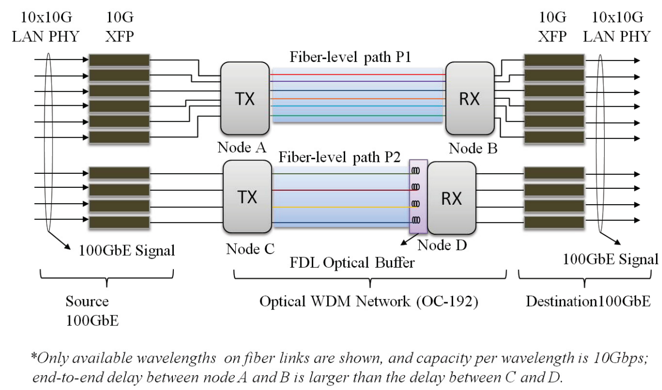

Fig. 1. Illustration of usage of FDLs in optical parallel transmission to counter differential delay issue

Figure 1 illustrates how Fiber Delay Lines (FDLs) can be used as optical buffers. Here, 10X10GbE signals are distributed to two fiber-level paths, referred to as P_1 and P_2. Path P_2 between node pair C and D is shorter than P_1, thus traffic routed on P_2 needs to be buffered at the receiver side in order to re-sequence the frames/packets to be the right frame order. Fiber Delay Lines (FDLs) "buffer" optical packets by adding extra delay to the shorter path with a selected fiber delay line [2]. In our example, FDLs at node D are utilized to compensate the differential delay between P_1 and P_2. However, a FDL buffer can only provide discrete delay (buffer) units, which is decided by the length of fiber per delay unit and presents a considerable practical limitation in its deployment.

In this paper, we propose to study the feasibility of Fiber Delay Lines (FDLs) for buffering in optical parallel transmission systems to support high speed Ethernet. To this end, we propose an optimization model based on Integer Linear Programming (ILP) to find wavelength routed paths with consideration of available FDLs in optical networks. In our model, we assume all-optical (wavelength continuous) channels, i.e., electronic processing only happens at source and destination nodes. As it has been shown before, ILP-based optimization models for multiple links are complex [3], [4]. Therefore, we use an Evolutionary Algorithm (EA) based approach to obtain optimal results. We show that utilizing FDLs can be feasible for optical parallel transmission and the technological restrictions imposed by the discrete size of FDL delay units can be overcome by optimally designed parallel routing. Our work is one of the very first attempts to explore the feasibility of parallel transmission using off-the-shelf optics.

The rest of the paper is organized as follows. Section II presents the related work. Section III presents a preliminary of FDL buffer and the proposed ILP model. This section also provides a brief overview of the Evolutionary Algorithm that is used in the paper. Section IV presents the performance evaluation. Finally, section V draws the conclusions.

II. Related Work

Formulating parallel transmission as an ILP problem is a variant of ILP models for multipath routing proposed in SONET/SDH networks [3], [4], [5]. In these models, a set of paths are usually computed in advance, which is used as an input to the ILP models to find an optimal solution, where any subset from the precomputed paths can be selected, in which the differential delay between the longest and shortest path is less than a given boundary. Srivastava et al. [3] also studied the differential delay compensation cost and pointed out that the memory cost for differential delay compensation should be considered. The required memory size is decided by the sum of difference between the longest path and all other paths, namely, the cumulative differential delay. Srivastava et al. [4] proposed two heuristic algorithms to route traffic into a group of virtual containers (VCs) which could satisfy the differential delay constraint in SONET/SDH networks. Ahuja et al. [5] studied the problem of minimizing the maximum differential delay in Ethernet over SONET networks.

Recently, optical parallel transmission is gaining attention from both academic and standardization communities. The Optical Transport Network (OTN) architecture specified in ITU-T G.709 has defined an optimum hierarchy to transport a variety of client signals over WDM networks, which is compatible to all the SONET/SDH data rates and is also suitable for the emerging high speed Ethernet (40/100Gbps Carrier Ethernet) [6]. Multiple Lane Distribution (MLD) has been proposed in IEEE 802.3ba that is compatible with OTN technologies, which strips high speed Ethernet signals are stripped into multiple Lanes [1]. An optimization framework that utilizes MLD to facilitate optical parallel transmission

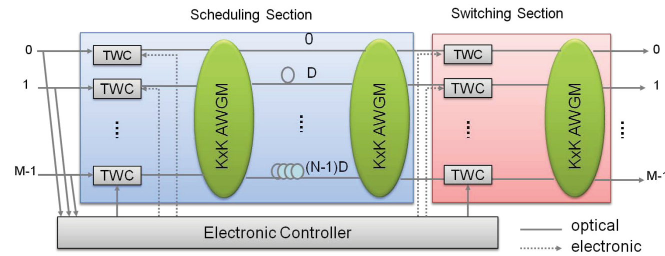

Fig. 2. An illustrative FDL buffer architecture [2]

have also been proposed with consideration of differential delay compensation [7]. Santos et.al. [8] proposed a multilayer optimization model based on ILP to find an optimal multipath routing solution in OTN layer; and proposed a heuristic for wavelength assignment in WDM layer. Santos et.al. [9] also presented an optimization model for multipath routing in OTN layer with consideration of differential compensation. It should be noted that none of the previous work addressed the impact of Fiber Delay Line (FDL) in optical parallel transmission.

III. Optimal Optical Parallel Transmission

A. Preliminary of Fiber Delay Lines (FDLs)

Fiber delay lines (FDLs) have been used as optical buffer, which deploys additional fiber to delay optical signals for "buffering". A delay unit is decided by the length of fiber deployed per unit. A representative FDL buffer proposed in [2] is shown in Figure 2. The granularity of each delay unit is denoted as D, and each fiber delay line can delay $n \cdot D$, $n = 0, 1, 2...N-1$. Traffic can not be circulated in the FDL buffer once it exits the line. The $K \times K$ AWG multiplexers (Arrayed-Waveguide Grating) enable the traffic from any input to be routed to any delay line with required delay units. The architecture shown in Figure 2 covers all principal features of FDL buffers. We therefore use it as a reference to formulate FDL constraints in the optimization. The ILP model is formulated to decide optimal number of FDL units required by each optical channel such that the differential delay can be minimized. The corresponding input-output ports are assigned during the duration of the connection and each fiber delay line can only be used by an optical path once.

B. Analytical Model

1) Notation: A WDM optical network is represented as $G(V, E)$, with vertices $v \in V$ and edges $e \in E$. All links in the network are equipped with the same number of wavelengths, denoted as W. The number of available wavelengths on link e is denoted as W_e and link delay is denoted as LD_e. It is assumed that capacity per wavelength is C. The connection request is denoted as $R(s, d, r)$ which specifies the source and destination nodes, i.e., (s, d), as well as the number of wavelengths (r) required to support a Carrier Ethernet service over a WDM network. All optical paths found for request R during the optimization are placed in a path set that is denoted as P. The ILP based optimization model relies on the following variables:

- $x_{p,w}$: Binary variable that denotes if the wavelength $w \in W$ is used by the path $p \in P$.
- $x_{p,e}$: Binary variable that denotes if the link e is used by the path $p \in P$, $e \in E$.
- $x_{p,w,e}$: Binary variable that denotes if the wavelength w in link e is used by the path $p \in P$, $w \in W_e$.
- $LD_{p,w}$: Integer variable that denotes the delay of the lightpath using wavelength $w \in W$ on an optical path instance $p \in P$ (becomes 0 if the wavelength w is not used on path p);
- $o_{p,p'}$: Binary variable that denotes if the path instance $p \in P$ and $p' \in P$ share at least a link.
- md: Integer variable which defines the floor of the maximal delay in current solution.
- n_{p,w,v,d_i}: Binary variable that denotes if the line d_i (the delay of line i is $i \cdot D$) in the FDL buffer in node v is used by $w \in W$ in path $p \in P$.

2) Multiple Wavelength Routing and Assignment: In our model, we assume that electronic processing only happens at the source or destination nodes. All lightpaths are established without wavelength conversion in the intermediate nodes, i.e., with wavelength continuity constraint. In the following, we first define the primary objective of the optimization which is followed by all the constraints.

Objective: The primary objective of this ILP model is to minimize the total resources used by the connection as defined in Eq.(1). The wavelengths taken in the fiber are weighted with the link delay for the preference of the shortest paths.

$$\text{minimize} \sum_{p \in P, e_{ij} \in E, w \in W} LD_e \cdot x_{p,w,e} \tag{1}$$

Routing constraints: We first define the routing constraints in Eq.(2). It ensures the incoming flow equal to the outgoing flow at each node, except for the source and destination nodes where the traffic was generate and ended, i.e.,
$\forall p \in P, v \in V:$

$$\sum_{e=(v_i,v_j) \in E} x_{p,w,e} - \sum_{e'=(v_j,v_k) \in E} x_{p,w,e'} = \begin{cases} -x_{p,w} & \text{if } v_j = s \\ x_{p,w} & \text{if } v_j = d \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

Additional constraints are introduced to prohibit the loops on the paths, i.e., to ensure that each node has at most one processor and and one successor (Eq.(3),Eq.(4)).

$$\forall p \in P, v_i, v_j \in V: \sum_{e=(v_i,v_j) \in E} x_{p,w,e} \leq 1 \tag{3}$$

$$\forall p \in P, v_j, v_k \in V: \sum_{e=(v_j,v_k) \in E} x_{p,w,e'} \leq 1 \tag{4}$$

Wavelength assignment constraints: The wavelength continuity constraint in wavelength assignment is implemented by defining the variable $o_{p,p'}$ which indicates if two paths share a common link. We introduce the constraint (5) to determine the value of $o_{p,p'}$ and the constraint (6) to ensure that if two paths share a link, they never share a wavelength, i.e.,

$$\forall p, p' \in P, p \neq p', e \in E: x_{p,e} + x_{p',e} - o_{p,p'} = 1 \tag{5}$$

$$\forall p, p' \in P, p \neq p', e \in E: x_{p,w,e} + x_{p',w,e} + o_{p,p'} \leq 2 \tag{6}$$

Bandwidth and capacity constraints: The constraint (7) ensures that the multipath solution can meet the requirement with regard to the number of wavelengths, and constraint (8) defines that the number of occupied wavelengths should not exceed available wavelengths on each link, i.e.,

$$\forall p \in P, w \in W, \sum_{p \in P, w \in W} x_{p,w} = r \tag{7}$$

$$\forall e \in E: \sum_{p \in P} x_{p,w,e} \leq W_e \tag{8}$$

Linearization: Note that a path is defined as $p = (e_1, e_2, ..., e_n)$ 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 non-linear, 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 $x_{p,e,w} = x_{p,e} \cdot x_{p,w}$. Whereas $x_{p,e,w}$ is determined by a non-linear function, we therefore define following constraints for linearization.

$$x_{p,e} + x_{p,w} - x_{p,e,w} \leq 1 \tag{9}$$

$$x_{p,e} - x_{p,e,w} \geq 0 \tag{10}$$

$$x_{p,w} - x_{p,e,w} \geq 0 \tag{11}$$

Electronic buffering: Electronic buffering constraints are provided here to present a benchmark for FDL buffering. In our model, we assume all network nodes are equipped with a small electronic buffer, denoted as M. We aim to show that whether integration of FDLs in parallel transmission can facilitate optical parallel transmission with a small electronic buffer. Delay of a lightpath is defined in Eq.(12). The value of md is defined in constraint (13) and the required electronic buffer is calculated in the left side of Eq.(14) which is constrained by the available buffer size M at destination node, i.e.,

$$\forall p \in P, w \in W: LD_{p,w} = \sum_{e \in E} LD_e \cdot x_{p,w,e} \tag{12}$$

$$\forall p \in P, w \in W: md \geq LD_{p,w} \tag{13}$$

$$C \cdot (md - LD_{p,w}) \leq M \tag{14}$$

Optical buffering (FDLs) constraints: Integration of FDLs changes the end-to-end delay of the path. Assume each FDL buffer has N fiber delay lines, the delay of a path with consideration of FDLs is defined in Eq.(15). The constraints for optimally utilizing available fiber delay lines are defined as follows. Eq.(16) ensures that a fiber delay line can only be assigned to one wavelength at a time. Constraint (17) ensures that one wavelength can use the FDL buffer at most once in one node, which is a restriction imposed by the FDL buffer architecture.

$\forall p \in P, w \in W, e \in E:$

$$pd_{p,w} = \sum_{e \in E} \{LD_e \cdot x_{p,e,w} + \sum_{i=\{1,..,N\}} (i \cdot D) \cdot n_{p,w,v,d_i} \cdot x_{p,e,w}\} \tag{15}$$

$$\forall v \in V p \in P, w \in W : \sum_{p \in P} \sum_{w \in W} n_{p,w,v,d_i} \leq 1 \tag{16}$$

$$\forall p \in P, w \in W, v \in V : \sum_{i=\{1,..,N\}} n_{p,w,v,d_i} \leq 1, i = \{1, .., N\} \tag{17}$$

C. Complexity Discussion

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 $O(|P| \cdot (|P| + |E| \cdot |W|))$. When the FDL constraints are considered, the complexity of the ILP optimization problem increases to be $O(2^n)$ where n is in $O(|P| \cdot (|P| + |E| \cdot |W| + |W| \cdot |V| \cdot |N|))$. When fiber delay lines are considered, the number of variable n_{p,w,v,d_i} that grows with increasing network size further enlarges problem size. This effect becomes more pronounced with an increase of the number of wavelengths per fiber in the network. Thus, the total number of variables in the optimization model is very high even for small networks. This complexity of the ILP prohibits the applicability the optimization model in practice.

D. Evolutionary Optimization

As discussed in the previous section, the complexity issue may lead to the the ILP formulation impractical in a realistic scale network topology. In this paper, we resort to an *Evolutionary Algorithm* (EA) based approached presented in [10] to obtain the solutions, while respecting all the linear constraints of the ILP formulation. It is a multi-objective optimization approach. We therefore transform the linear constraint that is formulated in Eq.(14) is to be the secondary objective, i.e.,

$$\text{minimize } max \sum_{p \in P, w \in W} C \cdot (md - D_{p,w}) \tag{18}$$

We hereby provide a brief overview of the EA approach used in this paper, and refer the reader to [10] for further details. The evolutionary multi-objective optimization utilizes the SAT decoding approach and starts from coding the binary variables introduced by the ILP model into chromosome space. Afterwards, a Pseudo-Boolean (PB) solver is used to find feasible solutions satisfying the necessary linear constraints defined by the optical multipath computation model. The value of the objectives are calculated and algorithm evolves to the next generation. In each generation, the inferior solutions are discarded from the solution space and the evolutionary operations such as crossover and mutation are carried out in the chromosome space to generate a new generation offspring for the evolution of the solutions. The evolutionary optimization stops after the pre-defined number of the generations' evolution.

IV. Performance Evaluation

In this section, we show the numerical results on a realistic scale network topology shown in Fig. 3 with link delay denoted in "Kilometers" [11]. We simulate a dynamic network environment with the assumption that all connection demands arrive independently and uniformly distributed among all node pairs. The number of wavelengths per fiber link is scaled down to 16 in order to reduce the simulation runtime. The number of wavelengths required by the connection demands are also scaled down accordingly. We assume that the connection requests vary from 1λ to 5λ. The number of connection demands is in inversely proportional to their bandwidth requirements, i.e., $1\lambda : 2\lambda : 3\lambda : 4\lambda : 5\lambda = 5 : 4 : 3 : 2 : 1$. For instance, assume there are 15 connection demands, the number of connections requiring 1λ and 2λ are 5 and 4. The number of other connection demands can be derived similarly.

The *load* A (in Erlang) in this evaluation is defined as $u * h * r/C$, where u is connection arrival rate and h is the connection holding time; r and C represent the average bandwidth requirement and the capacity of one wavelength respectively. The path set $|P|$ used in the results section depicts the maximal number of the fiber-level paths. For instance, $|P| = 2$ means the lightpaths of the connection demand can be established over two fiber-level paths, while $|P| = 1$ will restrict all lightpaths to be established over the same fiber links (single path). In this study, we assume each network node is equipped with a small electronic buffer with size of 5MB and a FDL buffer with an architecture illustrated in Fig.2. Each delay unit is assumed to have a delay of $D = 10us$ and the maximal number of delay unit of a fiber delay line is set to be 10, i.e., $N = 10$, i.e., each node can provide discrete delay of $0us, 10us, 20us...100us$. We aim to show that our model can optimally use available FDL buffers in an optical network to reduce the electronic buffering requirement, despite of the discreteness in delays.

We evaluate the proposed optimization model with and without FDLs constraints and compare the performance in both cases. When FDLs are considered, the path delay defined in Eq. (12) is replaced by the delay defined in Eq.(15). All other constraints, including routing, bandwidth etc. are the same in both cases. The simulation is performed for 2500 requests at each network load to derive a meaningful average value. All following solutions were obtained by the evolutionary approach implemented with the OPT4J framework [12]. The number of evolution generations to improve the parallel transmission solution is set to 150 with 25 individual offspring in each generation, which leads to a 3750 objective function evaluations per request.

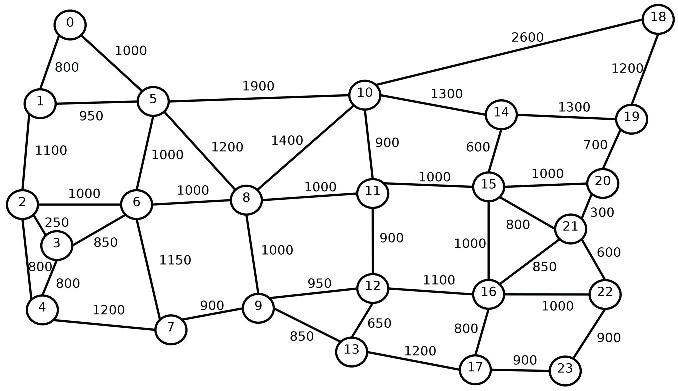

Fig. 3. Network topology used for the performance evaluation.

A. Quality of Solutions from EA-based Approach

Before evaluating the proposed optimization model on a realistic scale network topology, we first evaluate the quality of solutions obtained by EA based approach by comparing with solutions obtained from solving ILP directly. The evaluation 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. It is assumed 16 wavelength per fiber link and the arrival of traffic demands follow the same distribution as defined above. 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 multiple wavelength routing and assignment model with electronic buffering, i.e., constraints defined in Eq.(2) Eq.(14) are used. Both ILP and evolutionary optimization run 30 times each to derive an average value. For fairness of comparison, the same objective function defined in Eq.(1) is used in both cases.

The quality of an solutions is defined in terms of the normalized hypervolume [13]. The hypervolume of the optimal solution (or best solution) is set to be baseline of the normalization, i.e., the quality of the optimal solution equals to one. Therefore, the quality of a solution A is defined as $Hypervolume(A)\ /Hypervolume(Optimal/best)$. The results shown in Table I depict that the evolutionary optimization can yield solutions with same quality as ILP optimization 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 increasing network size, evolutionary optimization can find an optimal solution in a reasonable time.

B. Impact of Using FDLs in Optical Parallel Transmission

To assess the impact of using FDL instead of electronic buffers, we first study the resulting differential delay and buffer requirement of the solutions yielded from our optimization model. Fig.4 shows the average buffer requirements of the

TABLE I
THE QUALITY OF SOLUTIONS VS. DIFFERENT NETWORK SIZE

No. of Nodes	2	4	6	8	10	12
ILP $\|P\| = 1$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
EA $\|P\| = 1$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
ILP $\|P\| = 2$	1.0000	1.0000	1.0000	1.0000	1.0000	NaN
EA $\|P\| = 2$	1.0000	1.0000	1.0000	1.0000	1.0000	0.9985
ILP $\|P\| = 3$	1.0000	1.0000	1.0000	NaN	NaN	NaN
EA $\|P\| = 3$	1.0000	1.0000	1.0000	1.0000	0.9963	0.9864

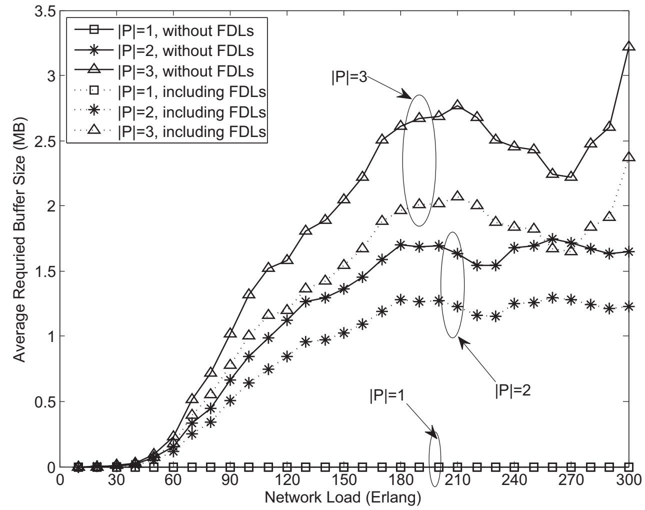

Fig. 4. Average buffer size vs. network load without and with FDLs

solutions. A larger $|P|$ requires a larger buffer due to the need to perform the frame re-ordering. However, all the solutions found require at most 3.3MB on average, which is within the bounds of available buffer size in the network, i.e., 5MB. The average differential delay increases with increasing $|P|$ as shown in Fig.5. The better illustrate the differential delay of the optimal solutions obtained from the presented optimization model, we take $|P| = 2$ as an example to illustrate the maximal differential delay of all the solutions and the average differential delay in Fig.6. It can be seen that the value of the maximum differential delay increases with the network load. However, a maximal value of $3000us$ has been observed in all the solutions with $|P| = 2$ is $3000us$, requiring 3.7MB buffer (refer to Fig.4) that is within the defined buffer constraint.

Fig. 5 and Fig.6 depict that the differential delay of the parallel transmission over diverse paths in optical layer is decreased with optimally utilizing FDLs, which leads to a smaller electronic buffering requirement. Fig.4 shows that the average buffer size required by the solutions is decreased by 30% for $|P| = 3$ and 20% for $|P| = 2$ at the high network loads (here, from $150Erl$ to $300Erl$). However, including FDLs only slightly reduces the bandwidth blocking ratio as shown in Fig.7. This is because the FDLs can only change the path delay in discrete time units, which has a limited positive impact on blocking since connections are more often blocked due to the bandwidth availability than due to the delay or buffer size constraints.

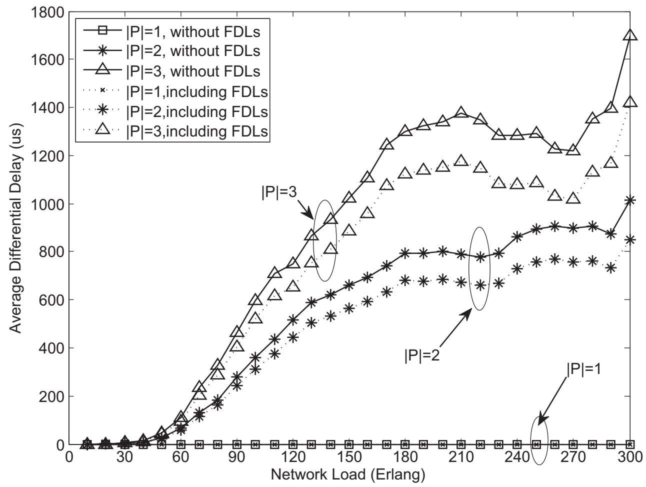

Fig. 5. Average differential delay of various $|P|$ vs. network load with and without FDLs.

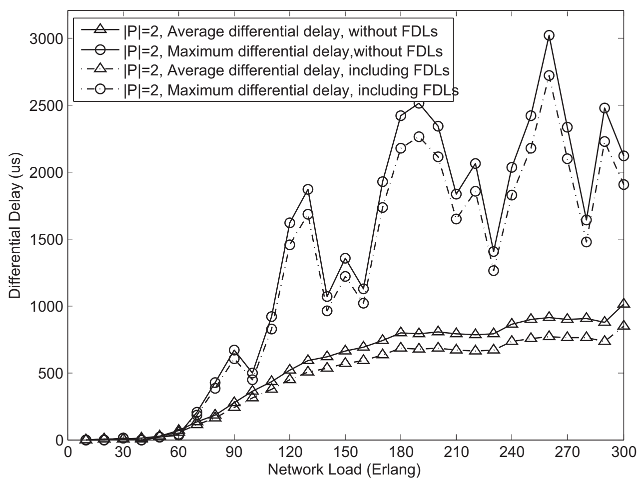

Fig. 6. Max. differential delay vs. network load without and with FDLs; $|P| = 2$.

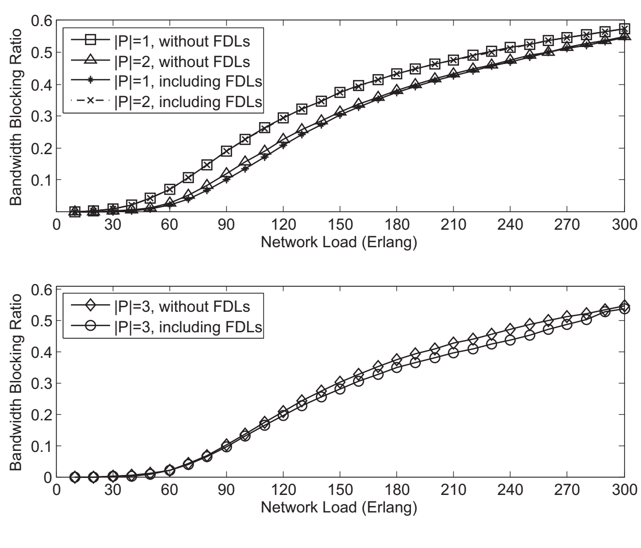

Fig. 7. The impact of FDLs on blocking vs. network load

V. Conclusion

In this paper, we presented an optimization framework with Fiber Delay Lines (FDLs) for optical parallel transmission to support high-speed Ethernet services. It allows inverse-multiplexing high speed Ethernet traffic into multiple optical paths and transferring in parallel. It is backwards compatible with the currently deployed optical networks, thus facilitating smooth adoption of Carrier Ethernet in transport networks.We formulated the problem of optimal usage of FDLs in optical networks an Integer Linear Programming (ILP) problem. The results obtained showed that discrete nature of delay provided by FDL buffers is not as limiting as expected, and that FDLs carry potential to enable optical parallel transmission without the need to provide large electronic buffers.

VI. Acknowledgment

This work has been partially supported by the European Commission through the GEYSERS project (http://www.geysers.eu) (FP7-ICT-248657).

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