A Joint Transmission Grant Scheduling and Wavelength Assignment in Multichannel SG-EPON

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***Abstract*—We investigate the problem of grant scheduling in multichannel optical access networks using a scheduling theoretic approach. The network we consider is a novel cost-effective Ethernet Passive Optical Network (EPON) that is designed to operate with STARGATE [2] or any evolutionary MAN. We show that the problem can modeled using an Open Shop model and we present a formulation for the joint scheduling and wavelength assignment problem as a Mixed Integer Linear Program (MILP) whose objective is to reduce the length of a scheduling period. Since the problem is shown to be NP-Hard, we introduce a Tabu Search based heuristic for solving the joint problem. Different other heuristics are also introduced and their performances are compared with those of Tabu and MILP. Results indicate that by appropriately scheduling transmission grants and assigning wavelengths, substantial consistent improvements may be obtained in the network performance.**

I. Introduction

There has been lately a strong worldwide push towards bringing fiber closer to individual homes and businesses. Fiber-to-the-Home/Business (FTTH/B) or close to it networks are poised to become the next major success story for optical fiber communications and hold great promise to enable the support of a wide range of new and emerging services and applications. These access networks are built as passive optical networks (PONs) which provide numerous advantages such as longevity, low attenuation, huge bandwidth, and cost sharing of feeder fiber infrastructure and optical line terminal (OLT) equipment among subscribers. PONs come in various flavors, with Ethernet PON (EPON) being currently installed worldwide [1]. Significant progress has been made in terms of cost reduction, multichannel upgrades of PONs by means of wavelength division multiplexing (WDM), and design of so-called colorless optical network units (ONUs), each connecting one or more subscribers to the PON [1]. Another development that is of particular interest is the cost effective integration of access and metro networks. An all-optical integration approach using low-cost passive but powerful optical devices is presented in [2], termed as STARGATE. STARGATE allows low-cost multichannel PON technologies to follow low-cost Ethernet technologies from EPON access networks into metro networks, resulting in significantly reduced costs and complexity. It further makes use of an overlay island of transparency with optical bypassing capability of OLTs. In short, STARGATE presents a cost effective architecture for integrating different multichannel access segments. Various ONU architectures are presented in [4], which allow STARGATE multichannel EPONs (termed as SG-EPONs) to evolve in a pay-as-you-grow manner while providing backward compatibility with legacy infrastructure and protecting previous investment. In such multichannel access network, resource scheduling and bandwidth allocation become a key issue for better managing these networks. Dynamic Bandwidth Allocation (DBA) algorithms for multichannel access networks typically consist of grant sizing and grant scheduling [3] methods, with extensive work done already on the former one. In this paper, we show that a straightforward transmission scheduling in multichannel SG-EPON optical access networks yields idle periods on the transmission channels and hence could result in poor resource utilization. We suppose that grant sizing is already predetermined using some existing method (e.g., [5] [6]) and hence we focus on grant scheduling. We assume a scheduling theoretic approach for solving the scheduling problem; we also consider an offline scheduling method wherein the OLT has complete information about the bandwidth requirements of the ONUs, through the Multi-Point Control Protocol (MPCP) [7]. We show that the transmission scheduling can be effectively modeled as an Open Shop (OS) problem and we model the joint problem of scheduling and wavelength allocation using Mixed Integer Linear Programming. Since the problem is shown to be *NP*-hard, when the number of channels is more than two, a heuristic method based on Tabu Search is presented for efficiently solving the scheduling problem.

II. Network Architecture and Related Work

Fig. 1 depicts the proposed SG-EPON architecture. The OLT is connected to the ONUs using a single feeder fiber link and a passive coupler at the remote node that splits and combines optical signals going to and coming from ONUs, respectively. A WDM coupler is placed on the shared feeder fiber link in order to guide long reach traffic across the metro to other long distant access networks; long reach traffic is transmitted across the metro through a Arrayed Waveguide Gratings (AWG) system [2] interconnecting different optical access segments. This is done by bypassing the OLT and connecting directly to the AWG of the passive star subnetwork of STARGATE, resulting in an all-optical single-hop path between these ONUs and thereby eliminating costly OEO conversions at the CO and OLT [2]. For increased flexibility, the SG-EPON may comprise different types of ONUs with different specifications and capabilities; namely, we distinguish between a TDM ONU, a WDM ONU and a Long

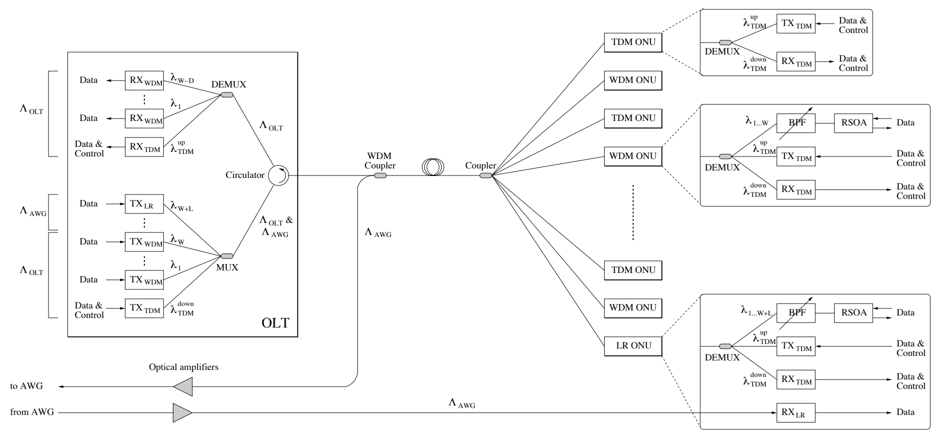


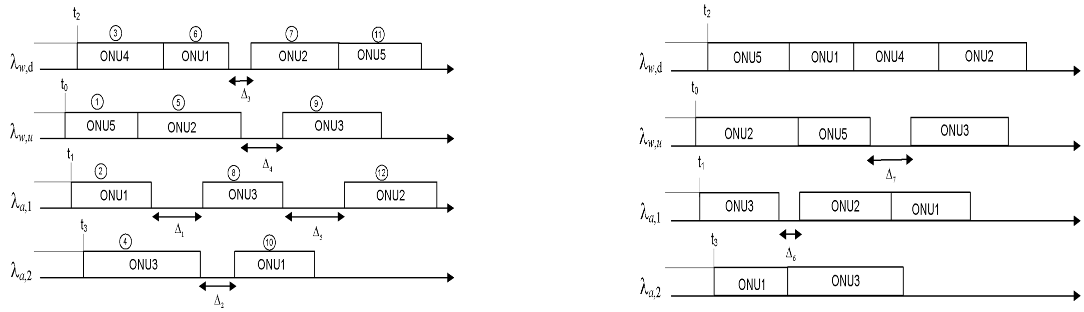
Fig. 1. SG-EPON single feeder-fiber network for smooth migration from legacy TDM ONUs to WDM-enhanced ONUs and long-reach (LR) ONUs.

Reach (LR) ONU. The TDM ONU is identical to that found in widely deployed legacy single-channel TDM EPONs. As shown in Fig. 1, a TDM ONU is equipped with one fixed-tuned transceiver to send/receive upstream/dowsntream data and control traffic to the OLT on wavelength channels λ_{TDM}^{up} and λ_{TDM}^{down} respectively. A WDM ONU has the same transmitting and receiving capabilities as the TDM ONU. In addition, a WDM ONU is designed to operate on multiple wavelengths. This could be achieved by installing an array of fixed-tuned transceivers, one for each upstream/dowsntream wavelength. Other alternatives are possible and have been studied with the design objective to achieve a more scalable ONU structure, while meeting low-cost cost requirements [8]. One of the most promising low-cost ONU design solutions is the one that uses a reflective semiconductor optical amplifier (RSOA) for remote modulation of upstream data [8], and is adopted for SG-EPON [4]. As shown in Fig. 1, a WDM ONU deploys an RSOA with a tunable bandpass filter (BPF) to select any of the $\triangle$ WDM wavelengths (Λ_{WDM}) $\lambda_1, \ldots, \lambda_\triangle$. Control traffic between OLT and WDM ONUs is sent on TDM channels for backward compatibility with IEEE 802.3ah MPCP [9]. A long-reach (LR) ONU has the same transmitting and receiving capabilities as a WDM ONU. In addition, a LR ONU has the capability of all-optically communicating to another LR ONU in a different or in the same SG- EPON (e.g., for bulk data transfer such as database synchronization or file sharing). A multi-wavelength receiver $\mathrm{RX_{LR}}$ operating on Λ_{AWG} wavelengths (Fig. 1) is used to enable receiving downstream data traffic coming from the AWG. Furthermore, the BPF of the RSOA is now tunable over the wavelengths $\lambda_1, \ldots, \lambda_{\triangle+L}$, where L denotes the number of additional wavelengths used for upstream transmission across the AWG. The OLT is also exposed to evolutionary add-ons to accommodate the upgrades of the shared media and of ONUs with respect to both hardware and software. The OLT is equipped with one fixed-tuned transceiver dedicated for downstream/upstream traffic on legacy wavelengths. In addition, an array of W fixed-tuned WDM transmitters plus L fixed-tuned long-reach transmitters is deployed to send downstream data as well as optical continuous wave (CW) signals (to be remotely modulated by the ONUs' RSOAs for upstream data transmission) on the wavelengths $\lambda_1, \ldots, \lambda_{W+L}$. The OLT deploys an array of $\triangle - D$ fixed-tuned WDM receivers to receive upstream data traffic on the wavelengths $\lambda_1, \ldots, \lambda_{\triangle-D}$, whereby D denotes the number of wavelengths used for downstream communication between OLT and ONUs.

Typically, dynamic wavelength and bandwidth allocation in multichannel EPONs consists of two subproblems, namely, grant sizing and grant scheduling [3]. Determining how much bandwidth each ONU can be allocated is referred to as the grant sizing (or bandwidth allocation) problem and various efficient DBA algorithms have been proposed over the past few years [5] [6] [11] [10]. The only work, which we are aware of, that considers the problem of grant scheduling is presented in [3]. The authors noted that the choice of scheduling framework has typically the largest impact on average queuing delays and achievable channel utilization. They assumed that grant sizing is done using some existing technique [5] [6] and focused on scheduling these grants for efficient upstream transmission. To achieve their objective, a layered scheduling approach is introduced which consists of a scheduling framework and a scheduling policy. The scheduling framework determines *when* the OLT makes scheduling decisions. A scheduling policy is a method for the OLT to produce a transmission schedule. The authors observed that each ONU can be viewed as a job, its grant size defines the processing time, and the channels used for transmission represent machines. Therefore, the problem reduces to scheduling a set of jobs, with specific processing times, to be executed on a set of machines with respect to some optimization criterion. Various underlying scheduling policies or their combinations are examined and the optimization objective is to minimize the queuing delay experienced by frames.

III. Motivation and Problem Statement

Our objective in designing a scheduler is to increase the achievable resource utilization and hence lower queuing delays. As mentioned earlier, instead of equipping each ONU (being WDM or LR) with an array of fixed-tuned or tunable transceivers, an RSOA is used for remote modulation of upstream data. In other words, the ONU uses one RSOA to either transmit or receive data on either WDM (for WDM- and



(a) NASC scheduling

(b) A more efficient scheduling

Fig. 2. Illustrative scheduling example

LR-ONUs) or AWG (for LR ONUs) wavelengths. Further, an ONU could either be in a receiving mode or a transmitting mode (the half duplex transmission property). Though it is cost effective, the use of one RSOA per ONU, together with the fact that an ONU may transmit/receive on multiple channels during a scheduling period, may lead to an inefficiency in utilizing the resources if the OLT does not produce an efficient transmission schedule. For illustration, we consider the scheduling problem illustrated in Figure 2(a) where offline scheduling framework is used along with Next Available Supported Channel (NASC) scheduling policy. Three LR ONUs ($ONU_{1,2,3}$) and two WDM ONUs ($ONU_{4,5}$) are considered for scheduling in a network with one upstream and one downstream WDM wavelength ($\lambda_{w,u}$, $\lambda_{w,d}$), two AWG wavelengths ($\lambda_{a,1}$, $\lambda_{a,2}$). We assume grant sizing has been determined; t_0, t_1, t_2, and t_3 designate the times wavelengths $\lambda_{w,u}$, $\lambda_{a,1}$, $\lambda_{w,d}$, and $\lambda_{a,2}$ become available respectively. The numbers in the circles designate the order of arrival of transmission requests from the corresponding ONUs (for upstream traffic) as well as other requests for downstream transmission on $\lambda_{w,d}$. Using NASC, it can be easily verified that the transmission schedule of the ONUs is as shown in Figure 2(a). It is to be noted that an ONU may transmit on multiple wavelengths, but only on one wavelength at a time due to the fact that there is only one RSOA at the ONU. Clearly, there are some gaps of idle periods ($\triangle_1$, $\triangle_2$, $\triangle_3$, $\triangle_4$, $\triangle_5$) during which none of the ONUs can transmit, although the channel is available, which will result in a longer schedule length and hence lower channel utilization. Instead, when the OLT has enough information about these requests, a more efficient scheduling policy may be used. It can be easily verified that the OLT can generate a more efficient (may not be optimal) schedule (Fig. 2(b)) by swapping some of the operations, which reduces the overall channel(s) idle time. This simple example illustrates the need for a more efficient scheduling policy, which is necessary for reducing these channel idle gaps to yield an efficient channel utilization with shorter schedule length.

IV. An Efficient Scheduling Policy

A. Preliminaries

Clearly, the selection of the scheduling policy is indispensable for achieving the desired objectives of superior system utilization. Our scheduling problem can be formulated using scheduling theory [12]. In scheduling terminology, the triple $\alpha|\beta|\gamma$ denotes a scheduling problem where α describes the machine environment (e.g., single machine, parallel machines, flow shop, etc.), β provides details of processing characteristics and constraints, and γ describes the objective to be minimized. Since in [3] all the channels are identical with the same speed/bandwidth, the scheduling problem has been modeled as identical machines in parallel where the objective is to minimize the un-weighted sum of the completion times [3]. In [3], each ONU may transmit on only one channel per scheduling period, and may support a subset of (or all) wavelengths. In SG-EPON, however, there are different requirements that make the parallel machine model unsuitable. We have two types of ONUs, some of them may be scheduled only on one, but any, wavelength in Λ_{WDM} and others on any wavelength in $\Lambda_{WDM} \cup \Lambda_{AWG}$. Further, a LR ONU may be scheduled on more than one wavelength during the same scheduling period for reaching different (LR) destinations. Additionally, any ONU may be receiving downstream and sending upstream traffic in the same scheduling period. This accordingly requires a more articulate scheduling discipline.

B. The Open Shop Problem, OSP

The open shop refers to a problem where there are n jobs and m machines, each job has to be processed on each one of the m machines. The OSP, with the objective of optimizing the maximum completion time, is denoted as $O_m||C_{max}$ [12]. Given n jobs $\{J_j|1 \leq j \leq n\}$ and m machines $\{M_i|1 \leq i \leq m\}$ where each job J_j is subdivided into m operations $\{O_{ij}|1 \leq i \leq m\}$, then operation O_{ij} must be performed on machine M_i and requires a processing time p_{ij}. Note that, in OSP each job J_j can be processed on only one machine at the same time and each machine M_i can process only one job at a time. In SG-EPON, each ONU_j may be viewed as a job J_j which needs to be executed; a transmission window (or grant) W_{ij} assigned for ONU_j for transmission on wavelength λ_i can be interpreted as an operation O_{ij} for job J_j on machine M_i and each ONU may have a list of grants $\{W_{ij}|1 \leq i \leq m\}$. The length of a grant t_{ij} can be viewed as the processing time (p_{ij}) of each operation (the terms operation, transmission grant or transmission window are used interchangeably). If an ONU either cannot transmit or is not scheduled on a wavelength, then

$t_{ij} = p_{ij} = 0$. Each wavelength λ_i is considered as a machine M_i and all machines have the same speed. Consequently, scheduling transmission grants in a multichannel SG-EPON can be modeled using the open shop (without preemptions) method, where the objective is to minimize the length of the scheduling period (or the maximum completion time, C_{max}). A rule referred to as Longest Alternate Processing Time first (*LAPT*) yields an optimal schedule for $O_2||C_{max}$ when there are only 2 channels and n ONUs. Under *LAPT*, whenever a channel is available, start processing among the ONUs that have not yet received processing on either channel, the one with the longest processing time on the other channel. According to this rule, whenever a channel becomes available, those ONUs that have completed their transmission on the other channel have the lowest priority on the channel just freed. Indeed, the *LAPT* rule may be regarded as a special case of a more general rule that can be applied to open shops with more than two machines; this rule is referred to as the *Longest Total Remaining Processing on Other Machines first* rule. Unlike LAPT, which can be solved in linear time, the more general rule does not always result in an optimal schedule. It can be shown [12] that $O_m||C_{max}$ is NP-hard when $m \geq 3$ and there exists an immediate lower bound, LB:

$$LB = \max\{\max_{1\leq i\leq m}\{\sum_{j=1}^{n} p_{ij}\}, \quad \max_{1\leq j\leq n}\{\sum_{i=1}^{m} p_{ij}\}\} \tag{1}$$

C. Mathematical formulation

We consider a multichannel SG-EPON network (we refer to it as the home network) with N ONUs; two types of ONUs are considered (LR and WDM). The bandwidth requirement for a WDM ONU j (in the home network) is $R_j^u(bps)$ for upstream and $R_j^d(bps)$ for downstream demands. A WDM ONU can transmit on any wavelength $\lambda_i \in \Lambda_w^u$ (U is the total number of upstream WDM channels) and receive on any wavelength $\lambda_i \in \Lambda_w^d$ (D is the total number of downstream WDM channels) where Λ_w^u and Λ_w^d are the set of upstream and downstream WDM channels. Note that a WDM ONU can either transmit or receive at the same time, since the ONU is equipped with one RSOA. Further, due to that same constraint, a WDM ONU can transmit on only one channel at a time and two ONUs cannot transmit/receive on the same channel at the same time (wavelength conflict constraints). In addition, we assume all the traffic for one WDM ONU is transmitted on only one WDM channel. A LR-ONU has similar bandwidth requirement and transmission/reception capabilities; further, a LR ONU may transmit/receive to other LR ONUs, located either on the same or on distant long reach SG-EPONs through the AWG network, as shown in Figure 1. Let M be the number of SG-EPONs connected through AWG and let f be the free spectral range (FSR) of the AWG router [2]. Hence, a subset of LR AWG channels (Λ_a^m, $|\Lambda_a^m| = f$) can be used to interconnect LR ONUs in the home network to other LR ONUs on another distant SG-EPON m, $m \leq M$; let Λ_a be the set of all AWG wavelengths. Denote by $R_j^{a,m}(bps)$ the upstream bandwidth requirement of a LR ONU j to another LR ONU in SG-EPON m. Note, a LR ONU does not use the RSOA for receiving the downstream traffic (coming from distant SG-EPONs). Similar to a WDM ONU, a LR ONU can transmit on only one wavelength $\lambda_i \in \Lambda_w^u$ or $\lambda_i \in \Lambda_a$ or receive on $\lambda_i \in \Lambda_w^d$ at a time. Additionally, two different LR ONUs (in the same home network) cannot transmit on the same channel at the same time. We assume the OLT, through the MPCP protocol, knows the bandwidth requirements of all ONUs in its home network. We also assume that, given the bandwidth requests from the ONUs, grant sizing is done through some existing algorithm, e.g., [5] [6] [4]. Denote by w_j^u (w_j^d) the bandwidth allocated for ONU_j according to its instantaneous data rate R_j^u (R_j^d) in the upstream (downstream) direction. For a LR ONU, denote by $w_j^{a,m}$ the bandwidth allocated for ONU_j according to its rate $R_j^{a,m}$. Similar to [3] [5] [6] [10], we assume the OLT performs grant sizing and grant scheduling per cycle on every channel in the network. The cycle length determines the minimum bandwidth guaranteed that can be assigned per ONU scheduled on a particular channel. The computed schedule is repeated every cycle (until the state of the network changes and hence another schedule is re-computed). We denote by C_i the length of a schedule (or completion time) on wavelength λ_i. The following variables s_{ij} and t_{ij} designate the start time of a transmission window W_{ij} and its length. Note that $t_{ij} = w_j^u$ if λ_i is assigned to ONU j for its upstream transmission. For wavelength assignment, we assume the channels are indexed as follows: $\Lambda_w^u = \{\lambda_1, ..., \lambda_U\}$, $\Lambda_w^d = \{\lambda_{U+1}, ..., \lambda_{U+D}\}$, and $\Lambda_a^m = \{\lambda_{U+D+(m-1)f+1}, ..., \lambda_{U+D+mf}\}$, $m = 1, .., M$; hence, $W = U + D + Mf$ is the total number of wavelengths. We define the following binary decision variables, which are needed for wavelength allocation:

$$\alpha_{ij} = \begin{cases} 1 & \text{if } \lambda_i \in \Lambda_w^u \\ & \text{is assigned to ONU } j \\ 0 & \text{otherwise} \end{cases}$$

$$1 \leq i \leq U, \; 1 \leq j \leq N.$$

$$\beta_{ij} = \begin{cases} 1 & \text{if } \lambda_i \in \Lambda_w^d \\ & \text{is assigned to ONU } j \\ 0 & \text{otherwise} \end{cases}$$

$$U + 1 \leq i \leq U + D, \; 1 \leq j \leq N.$$

$$\gamma_{ij}^m = \begin{cases} 1 & \text{if } \lambda_i \in \Lambda_a^m \text{ is assigned to (LR) ONU} \\ & j \text{ to reach SG-EPON } m \\ 0 & \text{otherwise} \end{cases}$$

$$U + D + (m-1)f + 1 \leq i \leq U + D + mf,$$
$$1 \leq j \leq N, \; 1 \leq m \leq M.$$

We now define at the OLT two sets of lists that compose the solution to the transmission scheduling problem; namely, the "ONU list" for each ONU, containing the order of sized transmission grants pertaining to this ONU, and a "channel list" for each wavelength, containing the order of transmission grants (from different ONUs) that need to be scheduled on this wavelength. We define a *sequence* to be the union of these two lists and a *schedule* as the exact times at which the grants are to be processed (i.e., their start times). A *sequence* is henceforth a set of permutations of grants and does nor contain specific scheduling information. Denote by Ω the set of all all feasible sequences. In the OSP, a sequence is said to be *feasible* if it is acyclic. We define the following scheduling binary decision variables ($x, y \in \Omega$):

$$x_{ikj} = \begin{cases} 1 & \text{if } W_{ij} \text{ immediately precedes} \\ & W_{kj} \text{ on ONU } j\text{'s list,} \\ 0 & \text{otherwise} \end{cases}$$
$$1 \leq i \neq k \leq W,\ 1 \leq j \leq N.$$
$$y_{ijh} = \begin{cases} 1 & \text{if } W_{ij} \text{ immediately precedes} \\ & W_{ih} \text{ on channel } i\text{'s list,} \\ 0 & \text{otherwise} \end{cases}$$
$$1 \leq i \leq W,\ 1 \leq j \neq h \leq N.$$

The joint problem of grant scheduling and wavelength assignment (**P**) is modeled as a mixed integer linear problem (*MILP*), where the objective is to minimize the makespan C_{max}:

$$\textbf{(P)} \qquad \textbf{min } C_{max}$$

(2) forces C_{max} to be no less than the transmission finishing time of any ONU on any wavelength.

$$C_{max} - s_{ij} \geq t_{ij},\ 1 \leq i \leq W,\ 1 \leq j \leq N, \tag{2}$$

(3) indicate that if W_{kj} is scheduled immediately after W_{ij} on ONU j's list, then W_{kj} can only start at time s_{kj} when W_{ij} finishes. In other words, the scheduled grants on ONU j's list can not overlap with each other.

$$s_{kj} - s_{ij} \geq t_{ij} - T(1 - x_{ikj}), \quad 1 \leq i \neq k \leq W,\ 1 \leq j \leq N, \tag{3}$$
$$s_{ih} - s_{ij} \geq t_{ij} - T(1 - y_{ijh}), \quad 1 \leq i \leq W,\ 1 \leq j \neq h \leq N, \tag{4}$$

Here, T is a very large positive integer. (4) indicate that if W_{ih} is scheduled immediately after W_{ij} on channel λ_i's list, then W_{ih} can only start at time t_{ih} when W_{ij} finishes. (5) and (6) imply that, in the set Λ_w^u (or Λ_w^d), at most one wavelength can be assigned to ONU j in each scheduling round. Constraints (7) set an upper bound on the number of AWG wavelengths for each LR ONU j such that at most one wavelength in each set Λ_a^m can be assigned to it.

$$\sum_{i=1}^{U} \alpha_{ij} = a_j, \quad 1 \leq j \leq N, \tag{5}$$

where $a_j = 1$ if $w_j^u \neq 0$ and $a_j = 0$ otherwise.

$$\sum_{i=U+1}^{U+D} \beta_{ij} = b_j, \quad 1 \leq j \leq N, \tag{6}$$

where $b_j = 1$ if $w_j^d \neq 0$ and $b_j = 0$ otherwise.

$$\sum_{i=U+D+(m-1)f+1}^{U+D+mf} \gamma_{ij}^m = c_j^m,\ 1 \leq j \leq N,\ 1 \leq m \leq M \tag{7}$$

where $c_j^m = 1$ if $w_j^{a,m} \neq 0$ and $c_j^m = 0$ otherwise.

As mentioned earlier, if ONU_j is scheduled for transmission on wavelength λ_i, then t_{ij} is the size of the granted bandwidth; otherwise, t_{ij} equals to 0. Accordingly, we define the following expressions (8)-(10):

$$t_{ij} = \alpha_{ij} \times w_j^u, \qquad 1 \leq i \leq U,\ 1 \leq j \leq N, \tag{8}$$
$$t_{ij} = \beta_{ij} \times w_j^d, \qquad U+1 \leq i \leq U+D,\ 1 \leq j \leq N, \tag{9}$$
$$t_{ij} = \gamma_{ij}^m w_j^{a,m}, \qquad 1 \leq j \leq N,\ 1 \leq m \leq M, \quad U+D+(m-1)f+1 \leq i \leq U+D+mf. \tag{10}$$

where $t_{ij} \geq 0$. Other constraints are added to linearize the definition of x and y; note that for a particular ONU_j, x_{ikj} determines the ONU list or the sequence of operations pertaining to ONU_j.

$$x_{ikj} + x_{kij} \leq 1 \tag{11}$$

(11) guarantee that for a particular ONU_j, either W_{ij} precedes W_{kj} or W_{kj} precedes W_{ij} but not both. (12) guarantee that operation or grant W_{ij} immediately precedes at most one other operation for the same job of ONU_j. Similarly, (13) guarantee that W_{kj} is immediately preceded by at most one other operation for ONU_j.

$$\sum_{k=1}^{W} x_{ikj} \leq 1, \qquad 1 \leq i \leq W, \quad 1 \leq j \leq N \tag{12}$$

$$\sum_{i=1}^{W} x_{ikj} \leq 1, \qquad 1 \leq k \leq W, \quad 1 \leq j \leq N \tag{13}$$

(14) guarantees that on ONU_j's list, there are exactly W operations/grants ($W_{ij}, i = 1..W$), each of these operations is immediately preceded by exactly one other grant, except the first one, which is not preceded by any. It is to be noted that the size of a grant assigned to ONU_j on some wavelength could be 0 if the ONU is not scheduled for transmission on that wavelength; however, the operation must still be included in ONU_j's list.

$$\sum_{i=1}^{W} \sum_{k=1}^{W} x_{ikj} = W - 1, \qquad 1 \leq j \leq N \tag{14}$$

Finally, it can be easily seen that $x_{iij} = 0$, $1 \leq i \leq W$, $1 \leq j \leq N$. In a similar manner, we can rewrite the constraints for linearizing the definition of y; for a particular channel λ_i, y_{ijh} determines the list of operations pertaining to λ_i's list. (15) guarantee on λ_i's list, either W_{ij} precedes W_{ih} or W_{ih} precedes W_{ij} but not both. (16) ensure that if W_{ij} immediately precedes W_{ih}, then W_{ij} cannot immediately precede any other operation on λ_i's list. (17) ensures that if W_{ij} immediately precedes W_{ih}, no other operation can immediately precede W_{ih}. (18) guarantee that on λ_i's list, there are exactly N grants (W_{ij} , $j = 1..N$), each of these grants is immediately preceded by exactly one other grant, except the first one, which is not preceded by any. As before, note that the size of a transmission window assigned to some ONU_j on λ_i may be 0 if the ONU is not scheduled for transmission on that channel; nonetheless, the operation must still be included in λ_i's list despite the fact that its processing time is 0.

$$y_{ijj} + y_{ihj} \leq 1 \tag{15}$$

$$\sum_{h=1}^{N} y_{ijh} \leq 1, \qquad 1 \leq i \leq W, \;\; 1 \leq j \leq N \tag{16}$$

$$\sum_{j=1}^{N} y_{ijh} \leq 1, \qquad 1 \leq i \leq W, \;\; 1 \leq h \leq N \tag{17}$$

$$\sum_{j=1}^{N}\sum_{h=1}^{N} y_{ijh} = N-1, \quad 1 \leq i \leq W \tag{18}$$

It can also be seen that $y_{ijj} = 0$, $1 \leq i \leq W$, $1 \leq j \leq N$.

V. A Tabu Search Approach

Indeed, enumerating all the possible feasible sequences in Ω makes the problem difficult to solve for optimality in reasonable amount of time. Instead of looking for the costly optimal solution, we now develop a heuristic method for solving the problem using a tabu search. We first present heuristic algorithms, known as dispatching rules, that can be used to build approximate feasible schedules for the transmission scheduling and channel allocation problem. These heuristics are characterized by different criteria used to generate a *sequence*. Note that, generally these rules do not yield optimal solutions except in some particular scenarios (e.g., LAPT for $O_2||C_{max}$).

1) NASC: The feasible solution is obtained by scheduling ONUs on each wavelength according to the NASC (*Next Available Supported Channel* [3]) rule; here, ONUs are scheduled on its supported channel that first becomes available.

2) LPT: The feasible solution is obtained by scheduling ONUs on each wavelength according to the LPT (*Longest Processing Time* [14]) rule; here, on each wavelength ONUs are considered in decreasing order of assigned grant size.

3) SPT: The feasible solution is obtained by scheduling ONUs on each wavelength according to the SPT (*Shortest Processing Time* [14]) rule; here, on each wavelength ONUs are considered in increasing order of grant size.

4) LRPT: The feasible solution is obtained by scheduling ONUs on each wavelength according to the LRPT rule (*Total Remaining Processing Time* [12]) rule; here, ONUs with the highest total size of unscheduled grants are considered first.

5) LTRPOM(Longest Total Remaining Processing on Other Machines first [12]): This is the more general counterpart of *LAPT*. Every time a wavelength is available, the ONU with the largest total size of unscheduled transmission window on other wavelengths, among all ONUs, is selected for scheduling.

A. Tabu Search Heuristic

The tabu search is an iterative heuristic optimization method based on local search techniques, which starts from a feasible solution and at each iteration moves to another, possibly better, solution trying to search unexplored regions of the solutions space and to avoid cycling. The new solution s' selected at each iteration of the procedure is the best one belonging to a given neighborhood $N(s)$, of the current solution s. The neighborhood generally contains all the solutions that can be obtained from s by means of simple modifications, or moves. A *Disjunctive Graph (DG) Model* is used to describe the open shop scheduling problem while stepping throughout the neighborhood and searching for s' [14].

1) Disjunctive Graph Model: The disjunctive graph model for $O||C_{max}$ is an undirected graph $G = (\Gamma, E_J \cup E_M)$ where Γ is a set of *vertices* and contains $V+2$ nodes, one associated with each operation, plus the start and the end of the overall Shop. The size of each grant (t_{ij}) is considered as the weight of the corresponding node, with the weights of the start and end nodes set to 0. E_J contains a number of *undirected edges*, each connecting a pair of vertices associated with grants of the same ONU. E_M also contains several *undirected edges*, each connecting a pair of vertices associated with grants that are scheduled on the same channel. In OSP, operations/grants of the same ONU may be processed in any order, hence one has to decide the orientation of the edges in both sets E_J and E_M, such that the resulting directed graph is acyclic, to obtain a *feasible* solution. The open shop can be solved by finding an acyclic orientation of G such that the length of the longest path, defined as the sum of the weights associated with the vertices visited by the path, form the start to the end node, is minimized. The length of the longest path is therefore the makespan and such path is known as the *critical path*. Figure 3 shows the representation of the feasible solution (Fig.2(a)), of the scheduling problem presented in section III, using the disjunctive graph. The vertices correspond to the different grants (of ONUs 1→5) to be scheduled on both WDM and AWG channels. For instance, v_1 in Figure 3 corresponds to the transmission grant of $ONU1$ on $\lambda_{u,w}$. Horizontal directed edges represent the sequence of operations of the same ONU on different channels and vertical directed edges represent the sequence of operations of different ONUs on the same channel. It is to be noted that in OSP, all machines are assumed to be idle before any operation of any job is processed. This however may not necessarily be the case for scheduling transmissions in SG-EPONs. As we can see in Figure 2(a) (and Figure 2(b)), all channels have different starting times, and finish times. We modify the definition of the DG as follows. Let t_s be the time when the OLT starts its computation for the next schedule and t_i ($t_i \geq t_s$) be the time channel λ_i is free for scheduling. We add to the disjunctive graph then dummy vertices, as many as the number of machines or channels (i.e., W), each represent a dummy operation on the corresponding machine. The weight of a dummy vertex (d_i) representing an operation on λ_i is set to $t_i - t_s$. The DG is then defined as $G = (\Gamma, E_J \cup E_M)$, where Γ contains $V + 2 + W$ nodes; E_J has the same definition as before, and also contains new directed edges emanating from the start node and incident on the dummy nodes. E_M maintains the same definition as before, in addition to new directed edges emanating from each dummy node to all operations on the same channel as well as to the terminating node.

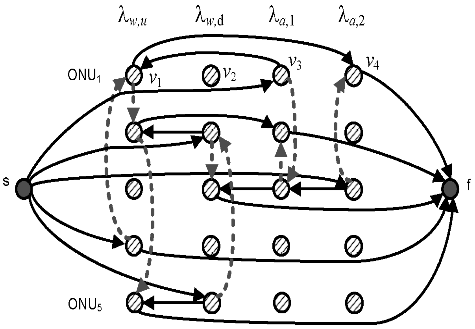


Fig. 3. Illustration of OSP using a Disjunctive Graph

2) Neighborhood Structures and Tabu Search: The first type of move we considered is as follows: the neighborhood s' of a current solution s is obtained by reverting the transmitting order of two or three consecutive critical operations or grants of the same ONU, or, alternatively, by reverting the transmitting order of two or three consecutive critical grants of different ONUs on the same wavelength. The term "critical" here refers to these grants that are on the critical path in the disjunctive graph which corresponds to s. The second type of move considers shifting operations of the same ONU on different wavelengths; for example, one ONU with upstream traffic may be assigned to any upstream wavelength in Λ_w^u. Hence, operations on upstream channels may be swapped from one channel to another in the same set. We perform similar moves on both downstream and AWG channels. These type of moves will yield to a feasible channel assignment along with a feasible sequence of operations. We note that such type of move does not exist for the original OSP since this latter does not involve any machine assignment and is only concerned with swapping operations on the same machine or swapping operations of the same job. Our tabu search algorithm consists then of performing a local search, using these above moves, to explore new feasible solutions; it also makes use of a short term memory (tabu list) that stores information associated with recently explored solutions in order to avoid cycling. Further, an aspiration criterion which allows to override the tabu status of a move is used, so that any move that yields better improvement is considered regardless of the status of the move [14]. Search diversification is obtained by allowing the algorithm to make restart and random perturbations. The algorithm restarts after executing λ iterations without any improvement on the current best solution. Periodic random perturbations (after γ iterations) are also used to enhance the diversification of the search.

VI. Performance Results

We implemented using C++ the tabu search procedure described above and the dispatching rules NASC, LRPT-LPT and LTRPOM-LPT. Note that, as in [15], we implemented the LPT as a secondary rule with LRTP and LTRPOM to break the tie. In our tabu search, we have used $\lambda = \{50N, 100N, 150N\}$ and $\gamma = 50N$ (N is number of ONUs), which are the algorithm restart and perturbation parameters (see [14]). Using these parameters, the execution of our Tabu search procedure did not exceed 6-10 minutes. Although shorter running time is feasible, it will slightly decrease the optimality of the solution found by Tabu. We also solved the $MILP$ model using CPLEX 9.1.3, for only small instances of the problem. We tested our tabu algorithm for different groups of experiments, by varying the number of ONUs as well as the number of wavelengths in each group. In the same group, we ran 5 experiments, randomly selecting each ONU's bandwidth requirement from 10% to 100% of its minimum guaranteed bandwidth(B_{min} [4]) on WDM upstream/downstream and AWG wavelengths [1]; we assumed a CBR traffic in all experiments. The configuration of these 5 experiments in each group is described as follows: for experiments 1 to 4 ($E_1 - E_4$), the bandwidth requirement is set to 10%-30%, 30%-50%, 50%-70% and 70%-100% of B_{min} for each ONU on both WDM upstream and AWG wavelengths; for the bandwidth demand on WDM downstream wavelengths, it was set to 5%-25% for each ONU in all of these four experiments, simulating a low WDM downstream traffic scenario. In E_5, however, these values are set to 70%-100% (demand on WDM upstream and AWG wavelengths) and 75%-95% (demand on WDM downstream wavelengths) for each ONU, respectively, to simulate a high WDM downstream traffic scenario. For each experiment, we ran tabu search for three times, each time the tabu procedure was initialized by feasible solution obtained from each dispatching rule as mentioned above. The best solution found among the three is output as the result of this experiment. The results of our experiments is listed in Table I. Our objective is to search for solutions with shorter/minimum makespan. In each group, as expected, simple rule such as NASC results in a solution with longer makespan. As indicated by "Difference" column, the performance gain of Tabu over the worst solution (e.g., NASC) varies from $9.3\% - 22\%$, and sometimes reach 29% (group 4). The LRPT-LPT and LTRPOM-LPT normally yields better performance than NASC, due to the fact that they tend to first schedule those ONUs with higher total traffic demands and larger transmission windows, and these rules generally tends to leave less gaps on each channel. As we we also see from Table I, in some instances they give as good a solution as tabu when the number of ONUs and wavelengths in the network is small (e.g., group 1) and the performance degrades otherwise. It is to be noted that Tabu only yields a local optimal solution. We obtained the global optimal after solving the MILP for small instances (e.g., 8 ONUs and (4,5) wavelengths); clearly, Tabu is able to achieve the optimal solution (in all instances Tabu achieved the LB derived earlier (which is a local LB)). Since the computation time for MILP is prohibitive, we did not run for larger instances. We can also observe from the tables that Tabu resulted in higher channel utilization (or less bandwidth waste) than the other scheduling methods due to its capability of reducing these idle gaps on the channels.

[1] Note that this B_{min} is calculated based on *limited service*, for those ONUs that request bandwidth larger than B_{min}, they will only be granted a transmission window size of B_{min}.

TABLE I
EXPERIMENT GROUP 1-4

Group 1 (8 ONUs, $U=1$, $D=1$, $M \times f=2$, $f=1$)									
	Make Span(ms)					Wasted Bandwidth (%)			
	NASC	LRPT-LPT	LTRPOM-LPT	Tabu	ILP	NASC	LRPT-LPT	LTRPOM-LPT	Tabu
E_1	0.51620	0.39538	0.42483	0.39538	0.39538	12.09	2.351	5.925	0.141
E_2	0.97406	0.79532	0.79532	0.79532	0.79532	5.717	0.144	0.144	0.144
E_3	1.28618	1.19526	1.19526	1.19526	1.19526	5.237	7.382	7.382	0.741
E_4	2.14242	1.83389	1.83389	1.63154	1.63154	10.260	11.410	11.410	3.154
E_5	1.85978	1.76347	1.76347	1.76347	1.76347	5.444	1.493	1.493	0.029
Group 2 (16 ONUs, $U=2$, $D=2$, $M \times f=2$, $f=1$)									
	Make Span(ms)				Difference	Wasted Bandwidth (%)			
	NASC	LRPT-LPT	LTRPOM-LPT	Tabu	(%)	NASC	LRPT-LPT	LTRPOM-LPT	Tabu
E_1	0.51830	0.47222	0.45199	0.42643	17.881	9.009	12.220	9.339	0.181
E_2	1.01854	0.89491	0.89491	0.89491	12.138	7.326	7.541	7.635	0.148
E_3	1.40407	1.26322	1.37664	1.26322	10.031	2.010	7.867	5.105	0.101
E_4	1.95798	1.75193	1.75314	1.75193	10.524	4.175	7.803	0.821	0.100
E_5	2.09691	1.93354	1.88098	1.71159	18.376	8.245	8.328	5.217	0.040
Group 3 (32 ONUs, $U=3$, $D=3$, $M \times f=4$, $f=1$)									
	Make Span(ms)				Difference	Wasted Bandwidth (%)			
	NASC	LRPT-LPT	LTRPOM-LPT	Tabu	(%)	NASC	LRPT-LPT	LTRPOM-LPT	Tabu
E_1	0.47531	0.43022	0.45199	0.43022	9.486	15.360	4.004	7.651	0.333
E_2	0.92024	0.83457	0.83457	0.83457	9.310	5.020	5.790	9.410	0.205
E_3	1.40834	1.23868	1.23868	1.23868	12.047	5.077	5.091	4.500	0.176
E_4	2.01564	1.71196	1.71196	1.71196	15.066	5.311	5.342	7.179	0.145
E_5	2.13869	1.75269	1.73888	1.68415	21.253	10.400	0.774	0.724	0.225
Group 4 (64 ONUs, $U=4$, $D=4$, $M \times f=8$, $f=2$)									
	Make Span(ms)				Difference	Wasted Bandwidth (%)			
	NASC	LRPT-LPT	LTRPOM-LPT	Tabu	(%)	NASC	LRPT-LPT	LTRPOM-LPT	Tabu
E_1	0.55764	0.43733	0.44567	0.42181	24.358	15.360	8.090	8.774	0.380
E_2	1.13675	0.90389	0.86562	0.82042	27.827	11.440	6.811	5.823	0.432
E_3	1.60878	1.36471	1.36883	1.25424	22.038	9.849	10.560	8.723	4.862
E_4	2.23747	1.80006	1.79460	1.73925	22.267	10.300	6.013	3.224	0.840
E_5	2.45252	1.98485	1.95966	1.73226	29.368	11.660	7.906	6.427	0.099

VII. CONCLUSIONS

We studied the problem of scheduling in multichannel access networks and we formulated our problem as an open shop.

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