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Wavelength-reuse in optical time-slotted networks☆

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ABSTRACT

An all-optical approach to achieve finer bandwidth granularity is to time division multiplex low capacity circuits on each wavelength channel and switch time–wavelength slots optically within the network. One such time-slotted network proposed in the literature is the Time Domain Wavelength Interleaved Network (TWIN), which eliminates slot switching within the network by using a non-reconfigurable core and an intelligent edge utilizing a fast tunable laser to emulate fast switching. In contrast to the TWIN, an optical time-slotted network which incorporates slot-switching within the network is the Time Wavelength Switched Network (TWSN), wherein the Time Wavelength Space Routers (TWSRs) are configured to change their routing pattern on a time-slot basis. The TWIN network assigns a unique wavelength to each node in the network and thus requires a total of $W = N$ wavelengths for an N-node network. We call such a TWIN network as an unconstrained TWIN network. In this paper, we first provide integer linear programs and heuristic algorithms to solve the scheduling problem for a static traffic matrix (of connections) for both, the unconstrained TWIN and the TWSN networks and also compare their performances under a dynamic traffic scenario. To address the problem of scalability of the unconstrained TWIN network, we propose to design a wavelength-constrained (i.e., $W < N$) TWIN network with no switching (TWIN-NS) by using a multicasting strategy. We also propose a variant of the TWIN network which possesses switching capabilities only at the edge nodes (TWIN-ES). Overall, this paper compares both versions of the TWIN networks to the TWSN network and investigates the benefits of having a reconfigurable core as opposed to a non-reconfigurable one.

1. Introduction

A drawback of conventional wavelength-routed optical networks is that of limited scalability and low channel utilization as it assigns an entire wavelength to a given session. This inefficiency can be reduced by adapting a time-slotted concept [1–4] to the wavelength-routed optical network, in which each individual wavelength is divided in the time-domain into fixed-length time-slots.

One such time-slotted network proposed in the literature is the Time Domain Wavelength Interleaved Network (TWIN) [5,6]. The network architecture of the TWIN avoids the use of fast reconfigurable switches by using non-reconfigurable wavelength routers. The router at every node is pre-provisioned to ensure that the optical signal on a given wavelength launched by a source will be routed to the intended destination. An example of such a device is the arrayed waveguide grating (AWG) [7,8]. Every edge node in the TWIN network is assigned a single fixed receiver (unique wavelength) and a tunable laser [9,10] to emulate fast switching of the data in the network. Nodes intending to send data to a particular node tune their lasers to the wavelength assigned to the destination node. Note that this TWIN network would essentially require $W = N$ wavelength channels for an N-node network and is not scalable. We refer to such a network as the unconstrained TWIN network.

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Another connection-oriented optical network that improves wavelength utilization is the Time Wavelength Switched Network (TWSN) [11,12]. In TWSN, time on every channel (wavelength) is slotted in a TDM fashion. A collection of such time-slots constitutes a time frame which repeats in time. The Time Wavelength Space Routers (TWSRs) are configured to switch time–wavelength slots. Note that unlike in Optical packet Switching [13–18] the switching pattern for each frame is predetermined during connection setup. In [11], we proposed several such TWSR architectures that incorporate wavelength conversion and fiber delay lines (FDLs).

In [5], a slotted network architecture was considered where a fixed size slot could accommodate a single burst. The aim of that work was to accommodate a given bursty traffic in as few slots as possible. The authors used a lower bound (obtained from the Birkhoff–von Neumann theorem [19] for a network without propagation delays) on the number of time slots required to clear the demand and presented a heuristic algorithm to compare the results while considering propagation delays. In this paper we consider a time slotted TWIN architecture to operate as a connection-oriented network. Our goal is to compare the performances of the TWSN and the TWIN networks. To that end, we first address the problem of optimally solving the scheduling problem for these networks for a given static traffic matrix (of connections) while taking into account link propagation delays. We present Integer Linear Programs (ILPs) to solve the scheduling problem and also develop heuristic algorithms. Secondly, we consider a dynamic version of a circuit switched network, wherein connection requests arrive to the network based on a stochastic arrival process. In the case of the TWIN network, the scheduling algorithm has to assign slots on all the links that span from the source to the destination. We note that these slots have to be assigned on the wavelength assigned to the destination. Hence in this case (TWIN) no connection wavelength assignment is needed. We use the shortest path algorithm to pre-provision all the non-reconfigurable routers in the network, and the First Available Slot (FAS) strategy to assign slots on all the links, to provision the connection request. In the case of the TWSN, unlike TWIN, we use fast optical switches which are capable of configuring their switching pattern on a time slot basis. This provision gives us flexibility of assigning any wavelength–slot to a connection request. We note however that the wavelength–slot must be available on all the successive links to the destination. Therefore in the TWSN, we have to solve not only the slot assignment, but also the wavelength assignment problem. In [20], it was shown that Least Loaded Wavelength (LLW) assignment performs better that other assignment algorithms. We therefore use the LLW strategy to solve the wavelength assignment problem and use FAS strategy to assign slots to the connection request.

To improve the scalability of the unconstrained TWIN network, the problem of *wavelength reuse* [21], in the TWIN network is addressed by using the multihopping strategy, whereby packets/connection slots are switched at intermediate nodes electronically towards their final destinations. O–E–O conversion destroys protocol transparency and increases switching costs. Furthermore, the problem of scheduling packets/connections in such a TWIN network is not addressed. In this paper, we present an all-optical method of designing a wavelength-constrained (i.e., $W < N$) TWIN network by using the multicast strategy [22,23]. We consider two types of TWIN networks: the TWIN network of [5], which has no switching capabilities (TWIN-NS) and a variant of the TWIN network which has partial switching capabilities at the edge nodes (TWIN-ES) that we propose here. We present an Integer Linear Program (ILP) which assigns a wavelength (not necessarily unique) to each node in the TWIN network while maximizing the network utilization, and also present ILPs to solve the connection scheduling problem in these TWIN networks. We compare these wavelength constrained TWIN networks to the TWSN network, which renders useful insight to the advantages one gains by using a reconfigurable switch (TWSR) as opposed to a non-reconfigurable core (TWIN). The proposed TWSN and TWIN networks can be implemented in regional or metropolitan areas where time–slot synchronization is possible. It is assumed that the nodes have the capability to synchronize the time slots on different arriving frames.

The remainder of the paper is organized as follows: Section 2 describes the operation of the TWSN and the unconstrained TWIN (i.e., $W = N$) networks. In Section 3, we describe the static traffic scheduling problem for these networks and present ILPs and heuristic algorithms. Section 4 compares the wavelength constrained TWIN-ES and TWIN-NS architectures to the TWSN network architecture and describes a TWIN-ES design problem. In Section 5, we present ILP formulations used to solve the design problem and for optimal connection scheduling in the wavelength-constrained TWIN network. In Section 6 we present simulation results and finally conclude the paper in Section 7.

2. Network architectures

In this section we describe the details of the TWIN and the TWSN networks and point out the main operational differences between them.

2.1. Time Wavelength Interleaved Network (TWIN)

The TWIN network uses non-reconfigurable wavelength routers in the core network to avoid fast switch reconfigurability. It achieves this by utilizing an intelligent edge node equipped with a tunable laser, which emulates fast switching. The core network comprises non-reconfigurable routers which are capable of routing incoming connections on a certain wavelength to a specific output port. The switching pattern for all the routers in the network is done *a priori*, by methods such as shortest path, spanning tree, etc. The TWIN network model assigns a *unique* wavelength to each receiver. Nodes that have data to send to a particular destination must tune their laser to the wavelength assigned to the destination.

Fig. 1 shows an example of an 8-node TWIN network. Node 1 has connections to be set up to nodes 6 and 8 respectively. It interleaves these connections on different