Slot synchronization in wavelength-routed star networks based on broadcasting frames from a multi-frequency laser

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Abstract: We propose and demonstrate a synchronization technique for wavelength-routed star networks. A multi-frequency tunable laser in a master node performs broadcasting function to synchronize the network nodes.

1. Introduction

Packet switching technique is widely used to provide efficient bandwidth utilization in network architectures such as passive optical network (PON), local area network (LAN) and supercomputer interconnection. In broadcast-and-select architecture based optical networks, the scalability is limited by the power budget due to the increasing losses associated by adding more splitting. Wavelength-routed star networks, whose core component is a centralized arrayed waveguide grating (AWG), have better scalability than broadcast-and-select networks based on passive couplers. This is due to the fact that the AWG has low insertion loss (3-6 dB) that is independent of the number of ports. The network nodes are connected to the AWG by fiber pairs. Each node is equipped with a tunable transmitter and a receiver that can receive signals of any wavelength. A node can send data to any other nodes by tuning wavelength correspondingly. A general architecture of wavelength-routed star networks is shown in Fig. 1.

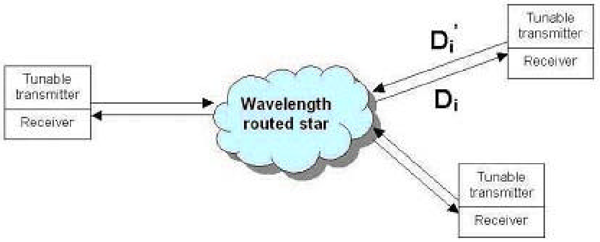


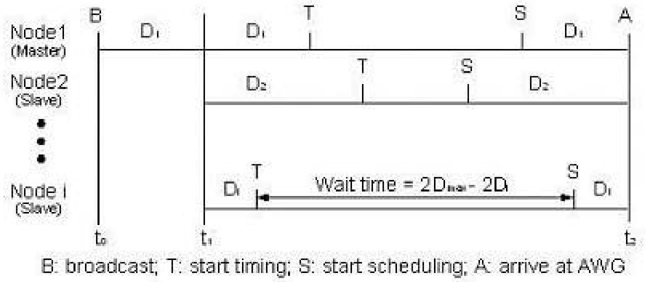
Fig. 1: A general architecture of wavelength-routed star networks

Synchronization of the packet-switched network nodes to avoid collision at the receiver end is an important issue in scheduled networks to provide high throughput. Data packets are encapsulated and switched in fixed-length time slots. Slot synchronization in previous demonstrations employ out-of-band signaling as the reference time and optical delay lines to finely adjust the packet arrival time. For example, a distributed slot synchronization (DSS) technique was demonstrated to implement global alignment for all time slots by using a subcarrier multiplexed channel to provide the reference time and a FPGA digital phase-locked loop for time slot alignment [1]. In addition, a packet synchronizer was developed using wavelength and space switching based on a tunable laser diode and eight semiconductor optical amplifier gates for each wavelength channel [2]. In this paper, we present a simple synchronization scheme using broadcasting frames generated from a multi-frequency laser (MFL) in a master node, which starts the timing of the network. The scheme uses in-band signaling therefore it does not require extra hardware for out-of-band signaling processing and delay adjustment. A proof-of-concept experiment is carried out to demonstrate synchronous packet switching in a 32 by 32-port AWG. Bit error rate (BER) is measured for data bursts with 2-μs length at 10 Gbit/s, and less than 1-dB penalty is observed compared with back-to-back measurement.

2. Principle

As shown in Fig. 1, the network nodes are typically placed at different locations from the central AWG. However, it can be reasonably assumed for a node i that the propagation delay of uplink fiber D_i is equal to that of downlink fiber D'_i since the two fibers are placed in the same cable in most applications. Data from different sources travel the same fiber from the AWG to node i. Therefore, it is only required that data packets are aligned at the input of the AWG to avoid collision at receiver end. Without fiber propagation delays, i.e., D_i is set to zero, the scheduling can be either preallocation or reservation style with fixed-length time slots to avoid collision at receiver end. If D_i is non-zero for the node, by adding a negative offset D_i to the start of the scheduling period of the node, slot synchronization can be achieved and the same scheduling algorithm can be utilized.

To implement this global timing alignment, we develop a master/slave protocol based on a MFL [3]. The MFL can operate as a tunable laser with sub-nanosecond tuning speed. Besides, it can also provide simultaneous multiple wavelength output, which is utilized to realize broadcasting function. Previously broadcasting of video/data services was demonstrated by spectrally tailoring broadband optical sources [4]. Before the protocol starts running, we assume the master node is designated. Each node has the following knowledge: the propagation delay to the AWG D_i, and the maximum propagation delay of the remotest node to the AWG D_{max}. The master broadcasts SYNC frames that are much shorter than a data packet to all the nodes in the network including itself. Upon receiving SYNC, the network nodes start timing. After waiting for $2D_{max} - 2D_i$, node i starts sending its data packets, which will arrive at the input of the AWG at the same time with packets from other nodes.



B: broadcast; T: start timing; S: start scheduling; A: arrive at AWG

Fig. 2 Time evolution of distributed synchronization protocol

Fig. 2 is a timing diagram for different network nodes. Suppose that node 1 is designated as the master node in the network. t_0 is the global time when the master node sends broadcasting frames SYNC, while $t_1 = t_0 + D_1$ is the global time that SYNC signals arrive at the AWG input. The SYNC signals with different wavelengths are routed to their corresponding destination nodes by the AWG. After $D_1 + D_i$, the SYNC arrives at node i. Then, node i starts timing and holds the data to be sent for a time duration of $2D_{max} - 2D_i$. The global time that node i starts to send data is $t_0 + D_1 + 2D_{max} - D_i$. Finally, the packets from different source nodes are aligned at AWG input at a global time $t_2 = t_0 + D_1 + 2D_{max}$.

Long-term synchronization is needed to avoid clock frequency discrepancy among the distributed nodes and propagation delay variation due to environment changes. In our scheme, instead of using out-of-band reference time, long-term synchronization can be implemented by inserting SYNCs in fixed intervals. Note that, the SYNCs may not need to be broadcast, but it has to be sent to all the nodes in the network periodically.

In the following section we perform an experiment that demonstrates two major functions of this wavelength-routed star network in the synchronization phase:

1. A master node broadcasts SYNC frames to all network nodes, including the master node itself.
2. A slave node receives the SYNC frame, waits for $2D_{max} - 2D_i$, and sends data to other nodes.

3. Experiment and results

The experimental setup is shown schematically in Fig. 3. The AWG has 32 by 32 input-output ports. However, for a proof-of-concept experiment, only two nodes are connected to the AWG to demonstrate the master/slave type of synchronization. Between the network nodes and the AWG, they are interconnected by conventional single mode fibers (SMFs). The fiber lengths used for node 1 and 2 are 8 km and 1 km, respectively.

In node 1 that plays the master role, the MFL outputs two wavelengths at 1553.3 nm and 1558.2 nm, respectively. At these two wavelengths, SNYC frames with the same pattern are generated by directly modulating the MFL. The inset in the figure shows the simultaneous two-wavelength signal output. The SYNC frame would contain flags, synchronization information and control field. However for this particular proof-of-concept demonstration, the SYNC frame is CW with duration of 200 ns to simplify data processing at the receiving ends. Therefore, in node 2 that is the slave node in the experiment, the receiver only detects the power of the quasi-CW light. The receiver output triggers a delay circuit. The circuit generates $2D_1 - 2D_2$ time delay, where D_1 corresponds to 8 km and D_2 corresponds to 1 km, respectively. The delayed trigger signal then initiates a tunable transmitter to send data to node 1 by tuning the wavelength accordingly.

Fig. 4a shows at node 1 the observed waveform of a data burst sent from the slave node. Node 2 is synchronized with node 1 by checking the delay circuit output and the master clock together using an oscilloscope. The SYNC frames are broadcast periodically. Node 2 generates 10-Gb/s data burst with 2µs-duration upon receiving of the trigger signal from the delay circuit. A zoom-in eye diagram is also provided in Fig. 4b. The data is generated from continuous pseudo-random bit sequence (PRBS) having a word length of 2^{31}-1. The data burst is obtained by chopping the PRBS to 2-µs length. The BER measurement is performed by gating the BER tester following the receiver in the master node. Fig. 4c shows the BER measurements, less than 1-dB penalty is observed through the AWG and after transmission. The penalty is possibly caused by the power transient of the packets.

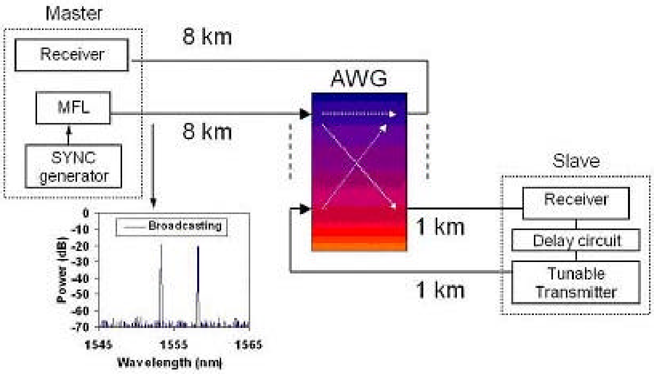


Fig. 3: Simplified schematic block diagram of the experimental setup.

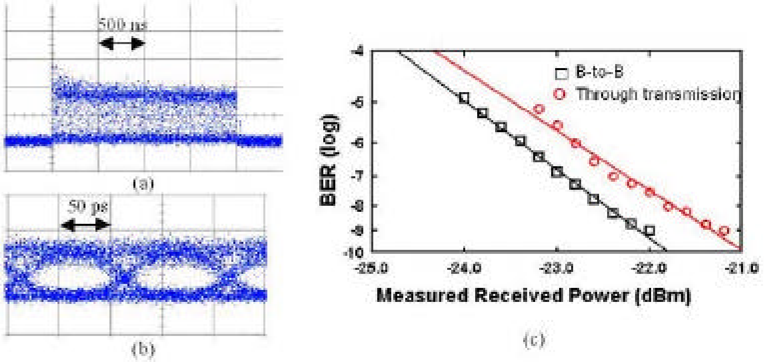


Fig. 4: a) Waveform of the 2-µs data burst sent from the slave node and received at the master node, b) A zoom-in eye diagram of the 10-Gb/s signal, c) BER measurements.

4. Conclusion

We present a simple synchronization scheme for wavelength-routed star networks based on broadcasting frames from a MFL. The scheme does not rely on out-of-band signaling or optical delay lines, therefore it reduces the hardware cost and simplifies the system design.

References:

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