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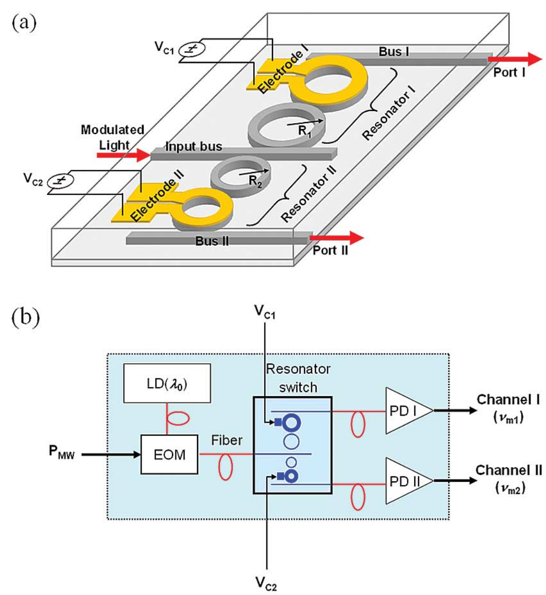

A photonic microwave channel selective filter incorporating a 1 × 2 switch based on two tunable polymeric cascaded ring resonators with different free-spectral ranges has been demonstrated, as seen in "Photonic Microwave Channel Selective Filter Incorporating a Thermooptic Switch Based on Tunable Ring Resonators," by G.-D. Kim *et al.*, p. 1008.

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Hybrid Multicast Mode in All-Optical Networks

Xin Liu, Hongxiang Wang, and Yuefeng Ji

***Abstract*—Although serial multicast mode (SMM) can increase the multicast success ratio (MSR) more than parallel multicast mode (PMM), it suffers from the signal impairment and the extra delay caused by the optical loop. In this letter, a novel hybrid multicast mode (HMM), which combines PMM and SMM, is proposed to mitigate those issues. Moreover, an HMM-based two-level-buffered all-optical multicast module is also proposed to further mitigate the signal impairment in this letter. Finally, with the simulations, a conclusion can be drawn that HMM can get higher MSR and lower average delay than both PMM and SMM.**

***Index Terms*—Networks, optical communication.**

I. Introduction

TRADITIONALLY, research of multicasting in all-optical networks has been focused on the issues of the parallel multicast mode (PMM), which is realized by a 1-to-n optical power splitter embedded in the optical switch matrix [1], [2] or a separated device producing n simultaneous optical multicast packets (OMPs) on n different wavelengths [3], [4]. To increase the multicast success ratio (MSR) and guarantee the quality of services of the multicasting, a novel serial multicast mode (SMM) was proposed in [5]. It can realize the copies of the input OMP exported serially.

However, in the SMM-based all-optical multicast module (AOMM/SMM), the extra delay and the signal impairments are incurred by the optical loop and the erbium-doped fiber amplifiers (EDFAs) [5]. Those issues limit the implementation of SMM in all-optical networks.

To reduce the signal impairment and the extra delay caused by SMM, a novel hybrid multicast mode (HMM) is proposed in this letter. It combines PMM and SMM, realizes the storage and duplication of the input OMP, and exports multiple copies each time. Differences among SMM, PMM, and HMM are illustrated in Fig. 1. Since each time there are multiple copies exported in HMM, the average extra delay caused by the optical loop will be lower than that of SMM.

The simplest way to realize HMM is to change the 1-to-2 optical power splitter of the AOMM/SMM to the 1-to-3 optical power splitter. As shown in Fig. 2(b), each time the OMP in the loop goes through the 1-to-3 optical power splitter, two copies will be exported from the HMM-based AOMM (AOMM/HMM). However, the signal impairment of the output OMPs from the AOMM/HMM is still the same as that from AOMM/SMM. To reduce the signal impairment, an HMM-based two-level-buffered AOMM (TB-AOMM/HMM) is also proposed in this letter. It can decrease the circulation times of the OMPs in the all-optical loop with the two-level fiber delay lines (FDLs).

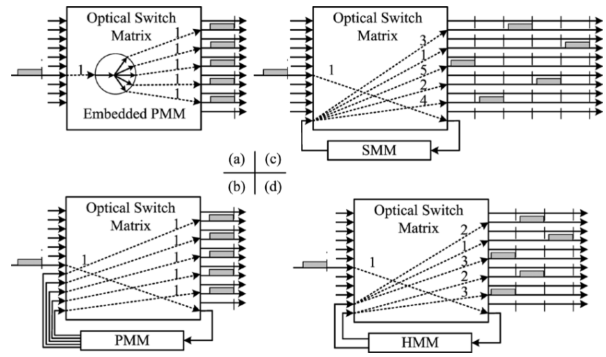

Fig. 1. Difference among PMM, SMM, and HMM. (a) Embedded PMM [1], [2]. (b) Separated PMM [3], [4]. (c) SMM [5]. (d) HMM. Numbers 1–5 are the operational steps of the optical switch matrix.

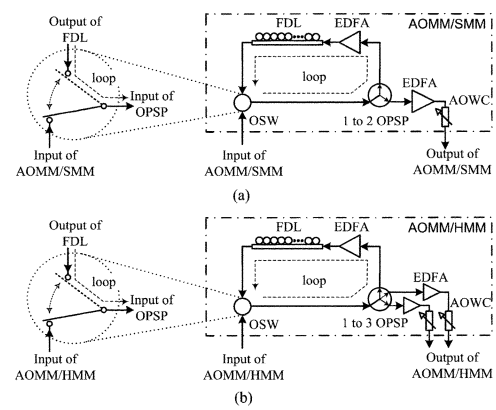

Fig. 2. Structures of the AOMM/SMM and the AOMM/HMM. (a) Structure of AOMM/SMM [5]. (b) Structure of AOMM/HMM. AOWC: all-optical wavelength converter. OPSP: optical power splitter. OSW: optical switch.

II. HMM-Based TB-AOMM/HMM

The structure of the TB-AOMM/HMM is shown in Fig. 3. It is made up of two all-optical wavelength converters, three EDFAs, a 1-to-3 optical power splitter, a 1×2 optical switch, two FDLs, a 3-dB coupler, and a 3-dB splitter.

The functions of the all-optical wavelength converters, EDFA, and 1-to-3 optical power splitter are the same as those in the AOMM/SMM. FDL_1 and FDL_2 are used to buffer the copies of the input OMP created by the 3-dB splitter and the 1-to-3 optical power splitter, respectively. In accordance with the latency of the FDL in the AOMM/SMM, the latency of FDL_1 should be longer than the sum of the length of the

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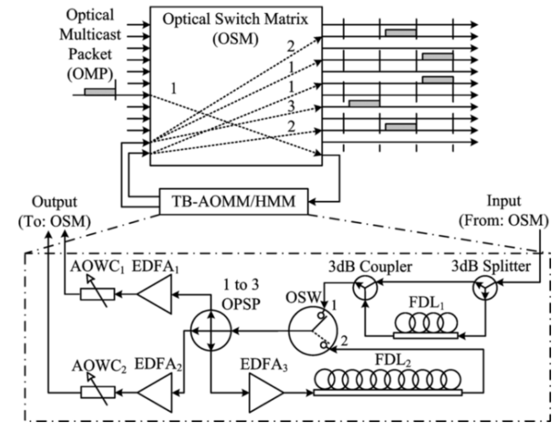

Fig. 3. Structure and application of the TB-AOMM/HMM. AOWC: all-optical wavelength converter. OPSP: optical power splitter. OSW: optical switch.

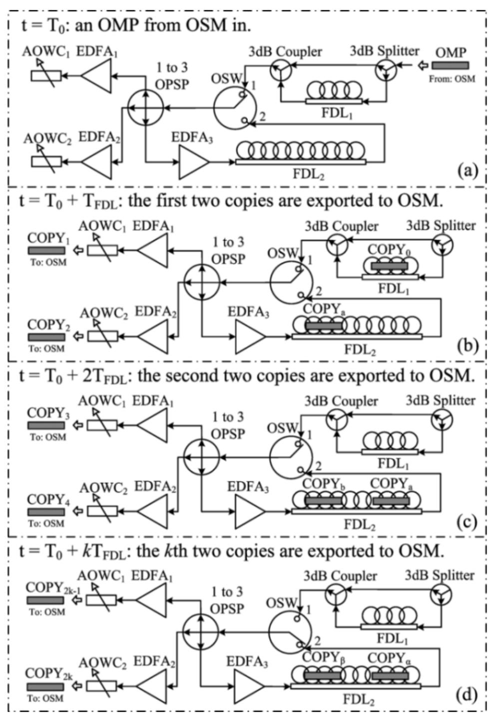

Fig. 4. Implementation of TB-AOMM/HMM. AOWC: all-optical wavelength converter. OPSP: optical power splitter. OSW: optical switch. T_{FDL} is the latency of the FDL_1.

maximal OMP in the network and the processing time of the multicast module. Concerning the latency of FDL_2, it is twice the latency of FDL_1. The optical switch is used to control the optical loop composed of the 1-to-3 optical power splitter, optical switch, EDFA_3, and FDL_2. When the TB-AOMM/HMM is available, the optical switch connects the input of the 1-to-3 optical power splitter with the output of the 3-dB coupler.

As described in Fig. 3, when an OMP arrives, it will be switched to the input of the TB-AOMM/HMM by the optical switch matrix of the local node. Then, as shown in Fig. 4(a), since the input of the 1-to-3 optical power splitter is connected with the output of the 3-dB coupler by the optical switch, after the OMP goes through the 3-dB splitter, one of the two copies created by the 3-dB splitter will be buffered in FDL_1 [COPY_0 in Fig. 4(b)], and the other will go through the 1-to-3 optical power splitter via the 3-dB coupler and the optical switch. When the copy goes through the 1-to-3 optical power splitter, three copies (COPY_1, COPY_2, and COPY_a) are generated, in which COPY_a enters FDL_2 and the other two copies are directly exported to the optical switch matrix via the EDFA and the all-optical wavelength converters, as shown in Fig. 4(b).

Then, COPY_0 starts to be exported from FDL_1. The same as the other copy which is not buffered by FDL_1, COPY_0 will go through the 1-to-3 optical power splitter via the 3-dB coupler and the optical switch. After time T_{FDL}, which is the same as the latency of FDL_1, another three copies (COPY_3, COPY_4, and COPY_b) are generated, in which COPY_b enters FDL_2 and the other two copies are exported. As shown in Fig. 4(c), since the latency of FDL_2 is twice that of FDL_1, when COPY_3 and COPY_4 are exported, there are two copies (COPY_a and COPY_b) being buffered in FDL_2. Before the first bit of COPY_a exported, the optical switch should be rearranged to connect the input of the 1-to-3 optical power splitter with the output of FDL_2 to construct the optical loop composed of the 1-to-3 optical power splitter, optical switch, EDFA_3, and FDL_2. Hence, with the two copies (COPY_α and COPY_β) in FDL_2 and the optical loop, the TB-AOMM/HMM will export two copies (COPY_{2k-1} and COPY_{2k}, which are the kth $(k > 1)$ output) each time until the loop is broken by the optical switch, as Fig. 4(d) shows.

Suppose that $(\mathrm{S/N})_0$ is the signal-to-noise ratio (SNR) of the input optical signal, δ is the noise figures of the EDFA, which is defined as the ratio of the input SNR to the output SNR of the EDFA, and i is the circulation times that the OMPs recirculate in the optical loop; based on the above illustration, we can obtain the SNR of the copy n exported from the TB-AOMM/HMM by (1). In addition, the SNR of the copy n exported from the AOMM/SMM and AOMM/HMM can also be obtained by (2) and (3), respectively,

$$(\mathrm{S/N})_n = \begin{cases} (\mathrm{S/N})_0 - (i+1)\times\delta, & n = 4i+1 \\ (\mathrm{S/N})_0 - (i+1)\times\delta, & n = 4i+2 \\ (\mathrm{S/N})_0 - (i+1)\times\delta, & n = 4i+3 \\ (\mathrm{S/N})_0 - (i+1)\times\delta, & n = 4i+4 \end{cases} \times \begin{pmatrix} i = 0,1,2,\ldots \\ n = 1,2,3,\ldots \end{pmatrix} (\mathrm{dB}) \tag{1}$$

$$(\mathrm{S/N})_n = (\mathrm{S/N})_0 - (i+1)\times\delta, \quad n = i+1 \quad \times (i = 0,1,2,\ldots)\,(\mathrm{dB}) \tag{2}$$

$$(\mathrm{S/N})_n = \begin{cases} (\mathrm{S/N})_0 - (i+1)\times\delta, & n = 2i+1 \\ (\mathrm{S/N})_0 - (i+1)\times\delta, & n = 2i+2 \end{cases} \times \begin{pmatrix} i = 0,1,2,\ldots \\ n = 1,2,3,\ldots \end{pmatrix} (\mathrm{dB}). \tag{3}$$

Fig. 5(a) plots the SNR impairment (decibels) against the output number of the copies from those multicast modules. From it, we can see that the signal impairment caused by the TB-AOMM/HMM is much less than that by the other two multicast modules, especially when more copies need to be exported.

Moreover, Fig. 5(b) plots the output number of the copies from those multicast modules against the circulation times of the OMPs recirculating in the optical loop. If we assume that SMM and HMM have the same tolerance of the signal impairment, which means that the maximum circulation times of the packets in SMM and HMM are the same, from Fig. 5(b), we can see that the TB-AOMM/HMM can export the most copies.

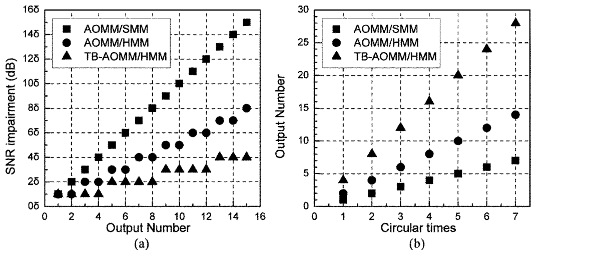

Fig. 5. Comparison of the signal impairment and the output number among AOMM/SMM, AOMM/HMM, and TB-AOMM/HMM. δ is the noise figure (NF) of the EDFA.

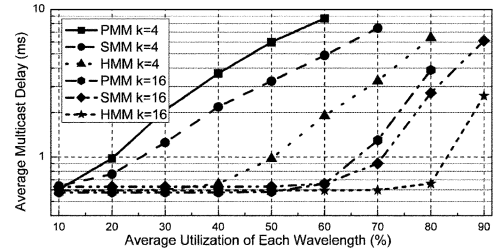

Fig. 7. Average transmission delay (AMD) comparison among PMM, SMM, and HMM. k is the number of the wavelengths in each downstream path.

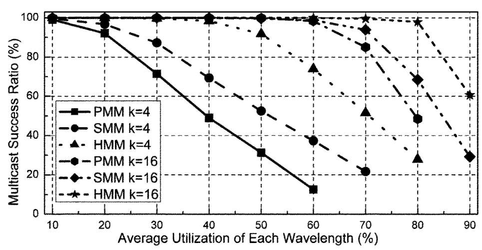

Fig. 6. MSR comparison among PMM, SMM, and HMM. k is the number of the wavelengths in each downstream path.

III. Performance Evaluations

In this section, MSR and the average multicast delay (AMD) among PMM, SMM, and HMM are investigated by simulations.

The network model, the traffic model, and the retransmission scheme we adopted here are the same as those in [5]. We consider the TB-AOMM/HMM in simulations and assume that the latency of its FDL_1 is the same as that of the FDL in the AOMM/SMM, which is defined as 10 μs long. To limit the transmission delay, the times of the copies of an OMP exported from the TB-AOMM/HMM are assumed to be the same as those from the AOMM/SMM, which means that SMM and HMM will have the same maximal extra delay.

The MSR is defined as the ratio of the number of the OMPs that have been received by all the destination nodes to the number of the OMPs that have been sent by the source node (including all the retransmitted packets). That is, if an OMP is received by all the destination nodes after three times of retransmission, the number of the OMPs that have been received by all the destination nodes is 1, the number of the OMPs that have been sent by the source node is 4, and the MSR is 25%. Simulation results are shown in Figs. 6 and 7.

It should be mentioned here that the higher simulation results (MSR and AMD of PMM and SMM) in this letter compared with those in [5] are due to the retransmission scheme. In detail, the retransmission scheme does not work adequately in [5] (although we defined the maximal retransmission times as 3 in [5], no packets are retransmitted twice or more times), and that is modified in this letter. With the modified scheme, more packets can be received by all the destination nodes under the same condition. That leads to the incompatibility of the simulations results between this letter and [5].

Since each time two copies are exported from HMM, the number of the total output copies from HMM is twice that from SMM. When copies are exported from the multicast module, if there is more than one downstream link available, one more OMP can be transmitted in HMM than in SMM. Then, the remaining downstream links where the multicast has not been implemented in HMM will be one less than those in SMM. With the following copies exported, the remaining downstream links in HMM will have more opportunities to be scheduled than those in SMM. Consequently, as Fig. 6 shows, HMM can obtain the highest MSR among the three multicast modes.

Fig. 7 shows the AMD comparison among PMM, SMM, and HMM. Although the maximal extra delay of SMM and HMM are supposed to be the same, since each time more copies are exported from HMM than SMM, multicast on more downstream paths will be implemented during the same period. In addition, since the MSR of HMM is higher than that of PMM and SMM, there are more OMPs that do not need to be retransmitted in HMM than in PMM and SMM. As a result, the AMD of HMM is lower than that of PMM and SMM.

IV. Conclusion

A novel HMM and an HMM-based TB-AOMM/HMM are proposed in this letter. With the illustrations and the performance evaluations, conclusions can be drawn that the TB-AOMM/HMM can mitigate the signal impairment with the two-level FDL and that HMM can achieve higher multicast ratio and lower AMD than both PMM and SMM.

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