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Performance Evaluation of the OCDM/WDM technique for Optical Packet Switches

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Abstract—The performance of the Optical Code Division Multiplexing/Wavelength Division Multiplexing (WDM/OCDM) technique for Optical Packet Switch is investigated. The impact on the performance of the impairment due to both Multiple Access Interference and Beat noise is studied. The Packet Loss Probability due to output packet contentions is evaluated as a function of the main switch and traffic parameters when Gold coherent optical codes are adopted. The Packet Loss Probability of the OCDM/WDM switch can reach 10^{-9} when M=16 wavelengths, Gold code of length L=511 and only 24 wavelength converters are used in the switch.

Keywords—Optical Code Division Multiplexing, Bufferless Optical Packet Switch, Performance Evaluation.

I. Introduction

THE switching speed of Internet router directly impacts the performance of the entire network. To improve switching speed and the bandwidth utilization, all-optical routers such as multiprotocol MPλS, Optical Packet Switching (OPS) and so on are proposed [1] to avoid the electricity switching bottleneck. MPλS [2] uses a wavelength as an optical channel in the router, but the capacity granularity MPλS may sometimes be too large to accommodate the traffic between node pairs. In the OPS [3]-[5], the label is attached to the head of a packet and routing of packets is based on label switching. The throughput is restricted because the packets are carried in serial on the same wavelength. Optical Code Division Multiplexing (OCDM) paths were proposed in [6]-[8] where each bit in the packet, including the header is encoded by a specific optical code. The OCDM paths can overlap with each other and that enables the router to process packets in parallel. To achieve satisfactory performance in the OCDM system, coherent time-spread optical-Code (OC) generation and recognition based upon Superstructure Fiber Bragg Gratings (SSFBG) using the gold code is employed [9]-[13]. The combination of OC- and wavelength-based routing has been presented in [6] where it is shown that the joint use of WDM/OCDM improves the efficiency of bandwidth utilization and obtains high flexibility in providing stable service owing to its independence of burst duration time and a simple architecture with nonbuffer operation.

In this paper we propose an analytical model, validated by simulation, to dimension the Optical Codes on any wavelength of a WDM/OCDM system so that the Packet Loss Probability due to both Multiple Access Interference (MAI) and beat noise is limited to a given threshold value. Next we evaluate the performance of a bufferless WDM/OCDM switch [14] using Gold Optical Codes dimensioned according to the proposed analytical model. The output packet contentions in the switch are solved in both the code and wavelength domains.

The organization of the paper is as follows. In Section II we describe the WDM/OCDM switch in question. The scheduling algorithm according to which the wavelength and code conversions are performed is described in Section III. We discuss the effectiveness of the WDM/OCDM technique in solving output packet contentions in Section IV. Our main conclusions and further research topics are discussed in Section V.

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II. WDM/OCDM Optical Packet Switch Architecture

We consider the WDM/OCDM optical packet switch with N Input/Output fibers (IF/OF) reported in Fig. 1. Each fiber supports M wavelengths denoted $\lambda_1, \cdots, \lambda_M$. On each wavelength up to F packets are carried out by using Optical Code Division Multiplexing. Let L be the code length and $\{OC_k, k = 1, \ldots, F\}$ the set of Optical Codes (OC) of a wavelength on which the packets can be carried. An input (or output) channel is identified by the triple (i, λ_j, OC_k), where i $(i = 1, \cdots, N)$ identifies one of the input (or output) fibers, λ_j $(j = 1, \cdots, M)$ identifies one of the wavelengths on that IF (OF) and OC_k $(k = 1, \cdots, F)$ identifies one of the optical codes on that wavelength.

The operation mode of the architecture is synchronous, meaning that all arriving packets have a fixed size and their arrival on each input channel is synchronized on a time-slot basis. The synchronization operation, not shown in Fig. 1, is realized by means of synchronizers located at the ingress of the switch.

The WDM/OCDM optical packet switch illustrated in Fig. 1 performs the following operations: i) the packets are wavelength demultiplexed and code decoded by means of one WDM demultiplexer and $M \cdot F$ OC decoders for each IF; ii) the unit control, not shown in Fig. 1, processes the packet headers and decides which packets have to be wavelength converted and which Output Wavelength Channels (OWC) and Output Optical Codes (OOC) are assigned to the packets to transmit; iii) the Switching Fabric SF_c routes the packets towards either the bank of r Wavelength Converters (WC) or the Output Switching Fabrics SF_i $(i = 1, \cdots, N)$ according to decisions taken by the control unit; iv) the converted packets are routed towards the SF_i $(i = 1, \cdots, N)$ where in output the packets are code and wavelength multiplexed by means of $M \cdot F$ OC coders and one WDM multiplexer.

One of the advantages of the proposed OPS is to reduce the number of WCs used because the control algorithm [15]

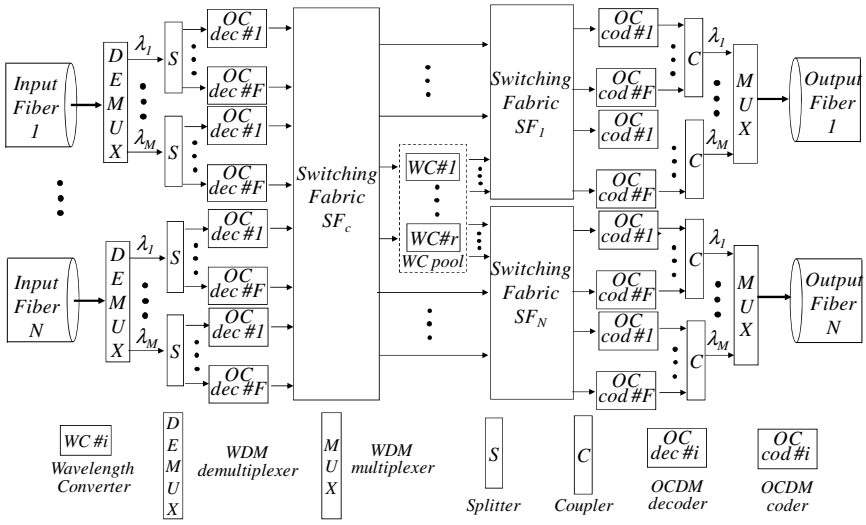


Fig. 1 WDM/OCDM Optical Packet Switch

first tries to solve the contention in code domain by changing the packet code and only if this operation is unsuccessful, the contention is solved in wavelength domain by using one WC of the shared pool. This strategy, preferring the use of passive devices like OC decoders and coders rather than active elements like WCs, allows for the reduction of the switch cost.

III. Control Algorithm in WDM/OCDM Optical Packet Switches

A flow chart of the Scheduling Algorithm (SA) executed in each time-slot for the WDM/OCDM Optical Packet Switch (OPS) is illustrated in Figs 2,3. The SA starts with the Initialization phase in which some sets and variables are initialized:

- $\Gamma \equiv \{1, \ldots, N\}$: the set of Output Fibers.
- $\Lambda_{i,j}$ $(i = 1, \ldots, N; j = 1, \ldots, M)$: the set containing the free output channels on $i-th$ OF carried out on the same wavelength λ_j. These channels are coded on F different OCs. The set is initialized to $\{(i, \lambda_j, OC_k)$ $k = 1, \ldots, F\}$ and it is updated during the execution of the SA when packets are scheduled for $i-th$ OF and wavelength λ_j.
- $I_{i,j}$ $(i = 1, \ldots, N; j = 1, \ldots, M)$: the set containing the packets arriving on wavelength λ_j, which are directed to $i-th$ OF and are yet to be scheduled. The $I_{i,j}$ $(i = 1, \ldots, N; j = 1, \ldots, M)$ sets initially contain packets arriving on wavelengths λ_j and directed to $i-th$ OF. They are updated during the execution of the SA when the packets are scheduled to be directed on the output wavelength channels.
- r_a: the available number of wavelength converters during the execution of the SA; it is initialized to r and decremented by 1 each time one of the converters is used.

After the Initialization phase, the control unit performs the packet scheduling operations. To allow for a fair assignment of the Wavelength Converters to the various OFs, these ones are randomly selected and for each of them the Code Conversion (CC) and Wavelength Conversion (WC) phases are performed. In CC phase, illustrated in Fig. 2, the packets that can be directed without wavelength conversion are scheduled and the contentions are resolved by changing the code. In WC phase, described in Fig. 3, the packet contentions are resolved in the wavelength domain by using the WCs.

In CC phase, for each wavelength λ_j $(j = 1, \ldots, M)$, the control unit randomly schedules up to F packets, chosen among the packets arriving on wavelength λ_j, to be transmitted without wavelength conversion. The set $\Lambda_{i,j}$ initially contains all the output channels on wavelength λ_j and optical codes OC_k $(k = 1, \ldots, F)$ which are used to forward without wavelength conversion up to F packets belonging to $I_{i,j}$ set. The following actions are performed by the control unit for each wavelength λ_j: i) one packet $\boldsymbol{a}$ and one output channel (i, λ_j, OC_k) are randomly selected from sets $I_{i,j}$ and $\Lambda_{i,j}$ respectively; ii) the packet is scheduled to be forwarded on output channel (i, λ_j, OC_k); iii) the sets $I_{i,j}$ and $\Lambda_{i,j}$ are updated by removing the elements $\boldsymbol{a}$ and (i, λ_j, OC_k) respectively. The CC phase complexity is $O(F \cdot M)$ because in the worst case at the least one operation for each output channel is performed.

In WC phase the control unit tries to forward with wavelength conversions the remaining packets on output channels not used in CC phase. The packets not scheduled and the free output channels for $i-th$ OF, are stored in I_i and Λ_i respectively. The following actions are performed by the control unit until either I_i or Λ_i (or both) are empty and one WC is available: i) one packet $\boldsymbol{a}$ and one output channel (i, λ_j, OC_k) are randomly selected from sets I_i and Λ_i respectively; ii) the packet is scheduled to be forwarded on output channel (i, λ_j, OC_k); iii) the sets I_i and Λ_i are updated by removing the elements $\boldsymbol{a}$ and (i, λ_j, OC_k) respectively; iv) the available number r_a of WCs is decremented by one.

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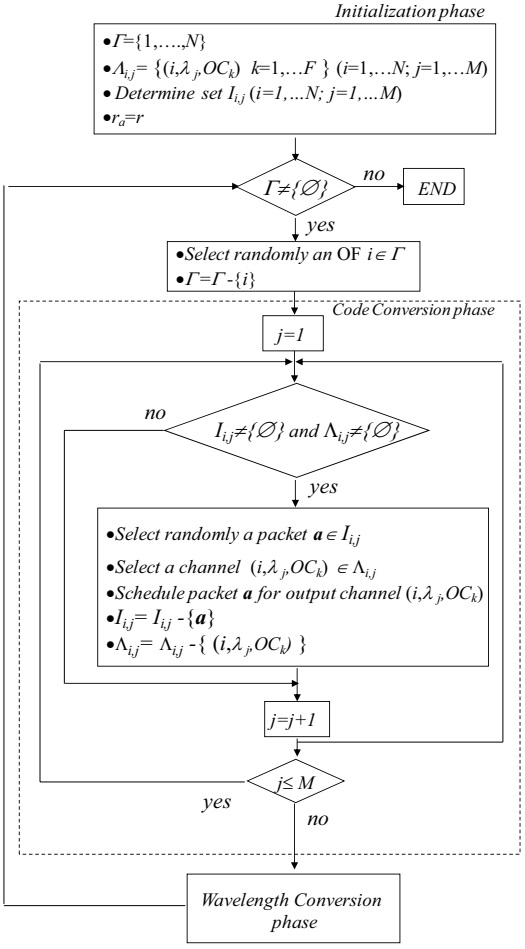


Fig. 2 Scheduling Algorithm in WDM/OCDM Optical Packet Switch; Initialization and Conversion Code phases are described

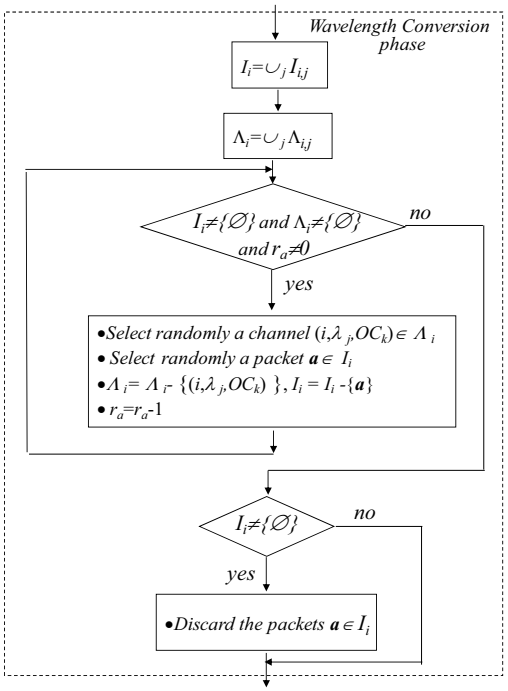


Fig. 3 Scheduling Algorithm in WDM/OCDM Optical Packet Switch; Wavelength Conversion phase is described

Before the end of WC phase, the control unit checks if there are packets in I_i which are yet to be scheduled and in this case they are discarded. The WC phase complexity is $O(min(r, M \cdot F))$ because in the worst case at the least one operation is performed for each output channel until WCs are available. Because the operations in CC and WC phases are performed for each OF, the computational complexity of the proposed scheduling algorithm equals $O(N \cdot F \cdot M)$.

IV. Numerical Results

This section will be devoted to illustrating the main results on the performance of WDM/OCDM switches as a function of the main traffic and switch parameters when the Optical Codes are dimensioned according to the procedures illustrated in [18]-[20].

First of all we show in Fig. 4 the Packet Loss Probability P_{loss}^{noise} due to MAI, Primary Beat Noise (PBN) and Secondary Beat Noise (SBN) versus the number F of OCs supported on each wavelength. Notice that P_{loss}^{noise} is the probability that at least a bit of a packet is affected by an error due to MAI and beat noise [15]. We have evaluated P_{loss}^{noise} for offered traffic p varying from 0,3 to 0,9 and packet length H equal to 500 bytes. The code length L is chosen to be 511. For each value of traffic we report two curves: the first one is obtained when the receiver threshold $th_i^{(s)}$ $(i = 2, \cdots, F)$, depending on the number i of packets carried on each wavelength, is evaluated according to the procedure illustrated in [15], the second one reports the results when the threshold $th_i^{(OT)}$ $(i = 2, \cdots, F)$ is chosen according to the procedure illustrated in [18]. From Fig. 4 you can notice how, when a given P_{loss}^{noise} is fixed, a higher number of codes can be carried on each wavelength if the receiver threshold optimization is performed. For instance, when p equals 0,5 and P_{loss}^{noise} is around 10^{-7}, we have that 4 and 10 codes can be carried on each wavelength in the cases in which the thresholds $th_i^{(s)}$ and $th_i^{(OT)}$ $(i = 2, \cdots, F)$ are used respectively.

The choice of an optimized receiver threshold impacts on the OCDM/WDM switch performance allowing for a reduction of the Packet Loss Probability P_{loss}^{opc} due to output packet contentions [15]. P_{loss}^{opc} is reported in Fig. 5 as a function of the number r of used WCs for H=500 bytes, N=8, M=16, L=511 and p=0,3, 0,5, 0,7. The number F of used OCs for each wavelength is chosen so that the threshold Packet Loss Probability P_{loss}^{noise} due to MAI and beat noise is not greater than 10^{-9}. For each value of traffic, we report P_{loss}^{opc} when the receiver threshold $th_i^{(s)}$ and $th_i^{(OT)}$ $(i = 2, \cdots, F)$ are used. We can notice that better performance is obtained when the threshold is chosen according to the procedure illustrated in [15]. For instance when p=0,7 and r=28, P_{loss}^{opc} equals $9,58 * 10^{-7}$ and $3,87 * 10^{-10}$ in the cases in which the receiver thresholds $th_i^{(s)}$ and $th_i^{(OT)}$ $(i = 2, \cdots, F)$ are used respectively. Obviously the better performance is due to the higher number of codes that is possible to carry on each wavelength and consequently a higher probability in solving

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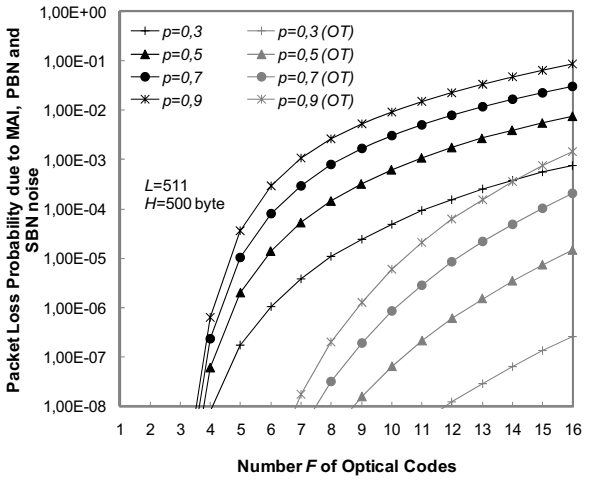


Fig. 4 Packet Loss Probability due to MAI and beat noise as a function of the number F of Optical Codes for L=511, H=500 byte and p varying from 0,3 to 0,9. The curves labeled with OT report the results when the Optimized Threshold is used

output packet contentions.

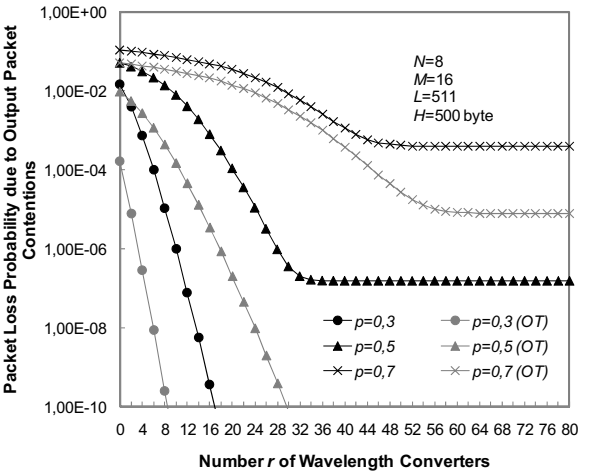


Fig. 5 Packet Loss Probability P_{loss}^{opc} due to output packet contentions as a function of the number r of used WCs. The curves labeled with OT report the results when the Optimized Threshold is used

V. Conclusion

The WDM/OCDM optical packet switch performance has been analytically investigated by introducing an analytical model to dimension the optical codes carried on each wavelength. The dimensioning has been performed in the cases in which a simple and an optimized receiver threshold are used. We have shown that the switch can reach acceptable performance, in particular for offered traffic p equal to 0,5, the packet loss probability equals 10^{-9} when the number M of wavelengths equals 16, the code length L is 511 and only 24 wavelength converters are used.

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