Performance evaluation of a WDM/OCDM based hybrid optical switch utilizing efficient resource allocation

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A hybrid optical switch (HOS) with physical layer of wavelength division multiplexing and optical code division multiplexing (WDM/OCDM) scheme is proposed. An additional feature to the HOS than optical cross connect (OXC) is that the controller can process requests for both circuit establishment and burst scheduling. In our study, the measurement criteria of HOS are the blocking probability, probability of error, and probability of outage. To simplify the analysis, no distinction is made between a circuit in progress and a burst in progress. Moreover, a minimum fit (MinF) resource allocation strategy is applied in order to increase the bandwidth efficiency and control the multiplexing interference of the OCDM. A 2D Markov model for the HOS is presented using the MinF strategy. Numerical results reveal that the code parameters and the resource allocation strategy greatly affect the performance. Certain periority can be achieved by assigning shorter codes to high periority users and longer codes to low periority users. Also, the probability of error and outage are reduced by appling the MinF strategy.

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The emergence of multimedia applications and fiber-to-the-home technologies elaborates the all-optical networking as a superior solution to meet that massive bandwidth demand. A switching technique with fine bandwidth granularity is required in order to fully utilize the capacity of all-optical networks. That is, the finer the bandwidth granularity, the better the bandwidth utilization. Optical circuit switching (OCS) as the first all-optical networking technique may not be flexible to convey bursty traffic and respond to dynamically varying loads and service diversity[1,2]. From the performance view point, optical packet switching (OPS) is rather ideal, but it is the most impractical switching technique because it requires high speed optical switches and bulky delay lines to support optical buffering of packets[3]. This motivates the idea of optical burst switching (OBS)[4].

OBS represents an intermediate solution between OCS and OPS, and combines the best of both techniques while avoiding their drawbacks. OBS can support bursty traffic generated by upper layers. The burst is the basic switching unit in OBS networks. The main idea in the OBS paradigm is the separation between the data and control planes. That is, the control packet (header) is sent on a dedicated control channel, and after a prespecified offset time, the data burst (payload) is sent on a data channel[5−8]. This offset time should be sufficient in order to avoid the need for optical buffers in OBS core nodes[9].

OBS networks utilize one way reservation signaling, which means that two or more bursts may content for the same output channel. Much research has been made for resolving the burst contention problem in OBS networks[10−14]. In this letter, optical code division multiplexing (OCDM) is employed to resolve that contention problem. Using hybrid WDM/OCDM as a physical layer, the available number of channels is increased and as a result, the blocking probability is reduced. The idea of hybrid optical switching can be applied in reality due to the available advanced technology. In Ref. [15], a gain-assisted plasmonic structure can achieve optical switching in the nano-domain and shorten the switching time to the sub-picosecond level. Their results depicted the potential application of the proposed structure in optical communication and photonic integrated circuits.

A so-called hybrid optical switching network is considered an alternative network architecture in which both OCS and OBS are used as the transmission mechanism[16−18]. Similar work has been made in the context of hybrid switching. In Ref. [19], hybrid packet and circuit switching is considered to be one promising technique in realizing high performance switching at low cost and less energy consumption. In that hybrid node, the scheduling complexity with typical scheduling algorithms may be reduced to half of a node running in full packet switching mode. The main difference between a hybrid optical switch (HOS) proposed here and an optical cross connect (OXC) is that the controller can accept and process both requests for circuits establishment as well as control packets for burst scheduling. The key motivation behind hybrid switching is to support both small flows (best-effort traffic) and large flows at the same switch[17]. Moreover, employing one hybrid switching network instead of having two separate networks enhaces the efficiency by reducing the maintenance and management overhead as well as increasing traffic multiplexing[18].

The proposed hybrid optical switch architecture is similar to that in Ref. [18] except that its physical layer is WDM/OCDM as depicted in Fig. 1. This means that each pair of wavelength and code (λ,C) denotes an optical channel assigned to the incoming request either for circuit establishment or control packet for burst scheduling. Note that an efficient resource allocation strategy can enhance the network efficiency and utilization. In this letter, a minimum fit (MinF) strategy, proposed by Beyranvand *et al.*[20], is applied to the hybrid optical switch network. In order to evaluate the performance of the proposed hybrid optical switch, the blocking probability and the probabilities of error and outage are evaluated, where the probability of outage P_{out} denotes the probability that the number of active OCDM codes in a chosen wavelength exceeds a predetermined threshold. A comparison between the MinF strategy and a conventional random fit (RanF) is presented to illustrate the superiority of MinF strategy applied in the proposed hybrid optical switch network.

Consider a single HOS in the optical network shown in Fig. 2. The switch controller for that HOS receives incoming requests in the form of control packets[17]. These control packets are related to circuit establishment or burst scheduling. Note that the incoming or outgoing links of the HOS may contain different number of fibers, each of bandwidth B. Employing WDM/OCDM as the physical layer for the HOS indicates that each fiber bandwidth is divided into N_{w} WDM windows and each window bandwidth is shared among N_{C} optical codes, as depicted in Fig. 1. Thus, the number of available channels in each fiber is $N_{\text{w}} \times N_{\text{C}}$. Each optical channel is represented by wavelength and code pair (λ,C). In this letter, the WDM/OCDM HOS is investigated regardless of the type of OCDM scheme, no matter whether it is coherent or incoherent. For simplification, the effect of the offset time in OBS and reservation signaling in OCS is ignored.

The idea of applying WDM/OCDM as a physical layer for HOS came from using it in a different technologies. Kitayama *et al.*[21] presented optical code based multi-protocol label switching, so-called OC-MPLS which ranges from circuit switching, burst switching, to packet switching. Khattab *et al.*[22] proposed a novel extension to the MPLS scheme that exploits a new physical layer (OCDM) for switching in optical GMPLS. So, an optical code switching layer is added to the existing label mapping layers. Also, Beyranvand *et al.*[23] presented a novel labeling scheme based on OCDM in GMPLS network.

Consider all the traffic flows coming from M input channels from a number of incoming links and are directed to outgoing links of K output channels such that $(0 < K \leqslant M)$, where loss can occur. The number of input and output channels, i.e., M and K, are calculated as

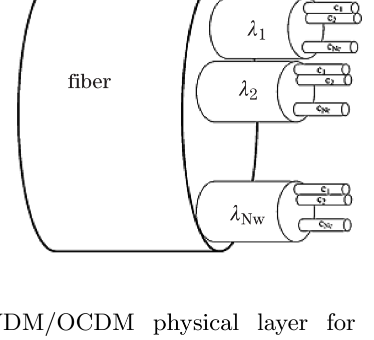

Fig. 1. WDM/OCDM physical layer for the proposed HOS[20].

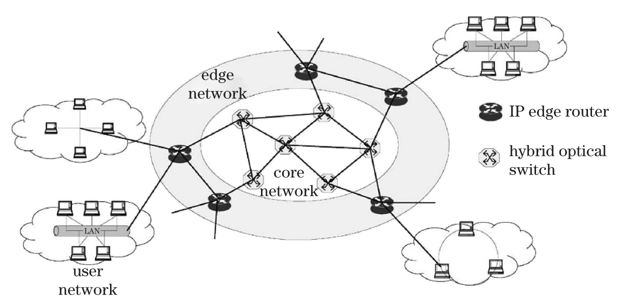

Fig. 2. Hybrid optical transport network architecture[18].

$$M = F_{\text{in}} \times N_{\text{w}} \times N_{\text{A}}$$

$$K = F_{\text{out}} \times N_{\text{w}} \times N_{\text{A}}$$

where F_{in} and F_{out} are the number of input and output fibers, respectively. Note that N_{A}, which is the number of allowable active users, is slightly smaller than N_{C}. N_{A} can be obtained considering the probability of error relation and the code parameters including the code length, code weight, and the maximum cross correlation[24,25].

A request for circuit establishment or burst scheduling arrives randomly on the input channels. If there is no available resources, the request is denied and the requested lightpath is not established or the corresponding burst is blocked. The blocked burst data needs to be retransmitted by a higher layer protocol such as the Transmission Control Protocol (TCP). Note that the time period during which the request is being served is called an ON period and the period between two successive ON periods is called an OFF period. During the ON period, the input channel (λ,C) is said to be active, and during the OFF period, it is said to be inactive. It is assumed that the ON and OFF periods are exponentially distributed, and the traffic streams on all input channels are statistically identical[18].

An input channel may carry bursts at some time, and may be allocated to circuits at other times. The total offered load ρ, which is λ/μ, is assumed to be $(0.5\rho_{\text{c}} + 0.5\rho_{\text{b}})$. It is assumed that the OFF period is exponentially distributed with mean $1/\lambda$ where $(\lambda = \lambda_{\text{c}} + \lambda_{\text{b}})$. Also, the ON period is exponentially distributed with mean $1/\mu$ where

$$\frac{1}{\mu} = \frac{1}{\mu_{\text{c}}} \cdot \frac{\lambda_{\text{c}}}{\lambda} + \frac{1}{\mu_{\text{b}}} \cdot \frac{\lambda_{\text{b}}}{\lambda}.$$

It is worthy to note that three traffic scenarios can be considered depending on the ratio of the circuit to burst traffic whithin the overall offered load as

1) for $\lambda_{\text{c}} = \lambda_{\text{b}} : \mu = \frac{4\mu_{\text{b}}\mu_{\text{c}}}{\mu_{\text{b}}+\mu_{\text{c}}}$,

2) for $\lambda_b = 2\lambda_c : \mu = \frac{6\mu_{\text{b}}\mu_{\text{c}}}{\mu_{\text{b}}+2\mu_{\text{c}}}$,

3) for $\lambda_c = 2\lambda_b : \mu = \frac{6\mu_{\text{b}}\mu_{\text{c}}}{2\mu_{\text{b}}+\mu_{\text{c}}}$.

Two classes of traffic are supported in the HOS. If no periority is given to any of the two classes, the standard Engset formula[26] can be applied to calculate the blocking probability. However, the Engset formula provides larger values of the blocking probability because it allows a new request to arrive without waiting for the total length of the burst to be dumped if this burst is blocked. In practice, when a burst is blocked at a switch, the input channel carrying that burst remains active until the end of the burst. The input channel is said to be blocked while the burst is being dumped. Therefore, an input channel can either be active, inactive, or blocked. On the contrary, there is no dumping for circuits and if the circuit is blocked, it is lost immediately.

An efficient resource allocation strategy can enhance the network efficiency and utilization, as stated earlier. The strategy of MinF is applied to the hybrid optical switch network in order to reduce the multiplexing interference (MI) in WDM/OCDM scheme. This is due to the fact that the probability of error is directly proportional to the number of active users in OCDM. Subsequently, the applied strategy chooses a WDM window with the minimum number of active users, and assigns one of its free codes. In order to highlight the superiority of the applied strategy, it is compared with a RanF strategy that randomly chooses a WDM window and assigns one of its free codes. The MinF in fact tries to uniformly distribute active users among WDM windows and, as a result, the probability of error is reduced[20]. Moreover, the probability of outage is also reduced. It denotes the probability that the number of active OCDM codes in a chosen wavelength exceeds a predetermined threshold.

The blocking probability is calculated using the same approaches used in Ref. [18,27,28]. In order to simplify the analysis, no periority is given to either circuits or bursts. Also, no distinction is made between a circuit in progress and a burst in progress in order to reduce the dimensionality of the problem. Let the set of doubles $\{(i,j): i=0,\cdots,K; j=0,\cdots,M-K\}$ denote the state of the approximate Markov process, where i is the total number of circuits and bursts in progress, and j is the number of blocked input channels. It is assumed that the OFF and ON periods are exponentially distributed with mean $1/\lambda$ and $1/\mu$ respectively, as stated before.

Let $\pi_{i,j}$ denotes the stationary distribution of the approximate Markov process. The transition rates are depicted in Fig. 3 for two cases. The local balance equation for case $i<K$ is written as

$$\begin{aligned}\pi_{i,j}[i\mu+j\mu_b+(M-i-j)\lambda] &= \pi_{i,j+1}[(j+1)\mu_b]\\ &+\pi_{i+1,j}[(i+1)\mu]\\ &+\pi_{i-1,j}[(M-i+1-j)\lambda]. \quad (1)\end{aligned}$$

The local balance equation for case $i=K$ is written as

$$\begin{aligned}\pi_{K,j}[K\mu+j\mu_b+(M-K-j)\lambda_b] &= \pi_{K,j+1}[(j+1)\mu_b]\\ &+\pi_{K,j-1}[(M-K-j+1)\lambda_b]\\ &+\pi_{K-1,j}[(M-K+1-j)\lambda]. \quad (2)\end{aligned}$$

Introducing the normalization equation $\sum_{i,j}\pi_{i,j}=1$ gives rise to a linearly independent system of equations, which can be solved to compute the stationary distribution. The total offered load is given by

$$T_\mathrm{o}=\sum_{i=0}^{K}\sum_{j=0}^{M-K}(M-i-j)\Big(\frac{\lambda}{\mu}\Big)\pi_{i,j}, \quad (3)$$

and the carried load is given by

$$T_\mathrm{c}=\sum_{i=0}^{K}\sum_{j=0}^{M-K}(i)\pi_{i,j}. \quad (4)$$

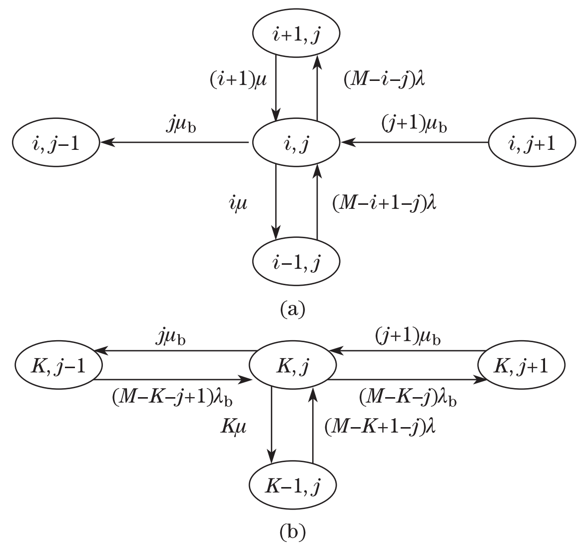

Fig. 3. State Diagram of HOS with no distinction between circuit in progress and burst in progress of (a) $i<K$ and (b) $i=K$.

An approximation of the blocking probability for both circuits and bursts is equal to

$$P_\mathrm{B}=1-(T_\mathrm{c}/T_\mathrm{o}). \quad (5)$$

The average probability of error is calculated using the same approach discussed in detail in Ref. [20]. It is assumed that $P_\mathrm{e}(a)$ is the probability of error for OCDM system which has an occupied codes or a active users. Thus, the average probability of error in WDM/OCDM-based HOS network is expressed as

$$P_\mathrm{e}=\sum_{a=1}^{N_\mathrm{C}}P_\mathrm{e}(a-1)P_\mathrm{A}(a), \quad (6)$$

where $P_\mathrm{A}(a)$ denotes the probability mass function (pmf) of the number of active users in each WDM window. Note that $P_\mathrm{A}(a)$ depends on the offered load and the kind of resource allocation strategy. The proposed HOS uses MinF resource allocation strategy. This means that when the signaling information arrives at the HOS node, it chooses a WDM window with the minimum occupied codes and assigns one of its free codes. If 2-WDM windows have the same number of occupied codes, it will randomly chooses one of them. $P_\mathrm{A}(a)$ is evaluated based on the 2D Markov model using MinF strategy[20] as illustrated in Fig. 4.

The code parameters affect the probability of error. $P_\mathrm{e}(a-1)$ of incoherent OCDM is given by[25]

$$\begin{aligned}P_\mathrm{e}(a-1)=&\frac{1}{2}\sum_{i=0}^{w}\Bigg\{((-1)^i\begin{pmatrix}w\\ i\end{pmatrix}\\ &\times\Big[1+\sum_{j=0}^{I_\mathrm{C}}\sum_{m=0}^{I_\mathrm{C}}(-1)^j\begin{pmatrix}i\\ j\end{pmatrix}\begin{pmatrix}w-m\\ m-j\end{pmatrix}P_\mathrm{m}\Big]^{a-1}\Bigg\}, \quad (7)\end{aligned}$$

where w is the code weight, I_C is the maximum cross correlation, and P_m is the probability of m hits between two codes and obeys the following equation[25]:

$$\sum_{m=0}^{I_C}m\begin{pmatrix}w\\ m\end{pmatrix}P_m=\frac{w^2}{2L}, \quad (8)$$

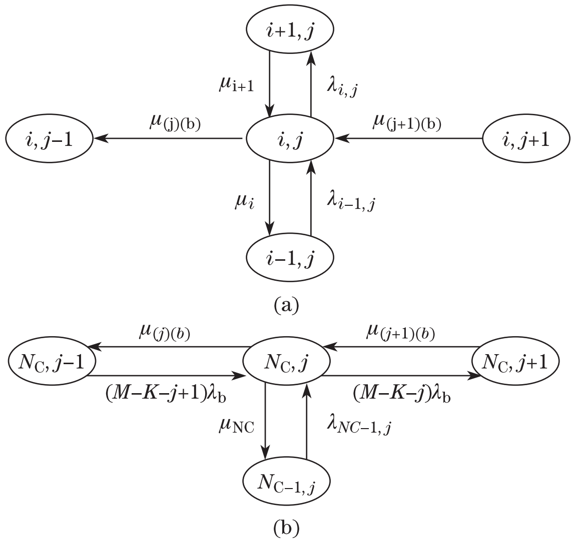

Fig. 4. 2D Markov model for a HOS using MinF strategy of (a) $i < N_{\mathrm{c}}$ and (b) $i = N_{\mathrm{c}}$.

where L is the code length.

From Fig. 4, i ranges from zero to N_{C} and j ranges from zero to $(M-K)$. The transition rates are calculated as

$$\begin{aligned}\lambda_{i,j} &= \lambda^{c}_{i,j} + \lambda^{b}_{i,j} \\ &= \sum_{n=0}^{N_w-1} \Big(\frac{\lambda}{N_w - n}\binom{N_w-1}{n}(N_{\mathrm{C}}-i)^n \\ &\quad \times \Big[M - j - (N_{\mathrm{w}} - n)i - \frac{n(N_{\mathrm{C}}+i+1)}{2}\Big]\Big), \quad (9)\end{aligned}$$

$$\mu_{i+1} = \sum_{j=2}^{N_w}\sum_{a_j=0}^{N_{\mathrm{C}}}(i+1)\mu = (N_{\mathrm{C}}+1)^{(N_{\mathrm{w}}-1)}(i+1)\mu, \quad (10)$$

where $\frac{1}{\mu} = \frac{1}{\mu_{\mathrm{c}}}\cdot\frac{\lambda_{\mathrm{c}}}{\lambda} + \frac{1}{\mu_{\mathrm{b}}}\cdot\frac{\lambda_{\mathrm{b}}}{\lambda}$.

The local balance equation of the Markov model in the case of $i < N_{\mathrm{C}}$ is

$$\begin{aligned}\pi_{i,j}[\lambda_{i,j} + \mu_i + \mu_{(j)(b)}] &= \pi_{i-1,j}[\lambda_{i-1,j}] + \pi_{i+1,j}[\mu_{i+1}] \\ &\quad + \pi_{i,j+1}[\mu_{(j+1)(b)}]. \quad (11)\end{aligned}$$

Similarly, the local balance equation in the case of $i = N_{\mathrm{C}}$ is

$$\begin{aligned}&\pi_{\mathrm{NC},j}[\mu_{(j)(b)} + \mu_{\mathrm{NC}} + (M-K-j)\lambda_{\mathrm{b}}] \\ &= \pi_{NC-1,j}[\lambda_{NC-1,j}] + \pi_{\mathrm{NC},j+1}[\mu_{(j+1)(b)}] \\ &\quad + \pi_{NC,j-1}[(M-K-j+1)\lambda_{\mathrm{b}}]. \quad (12)\end{aligned}$$

Introducing the normalization equation $\sum_{i,j}\pi_{i,j} = 1$ gives rise to a linearly independent system of equations, which can be solved to compute the stationary distribution. Then, the probability mass function of the number of active users in each WDM window is obtained by

$$P_{\mathrm{A}}(a) = \sum_{j=0}^{M-K}\pi_{a,j} \quad 0 \leqslant a \leqslant N_{\mathrm{C}}. \quad (13)$$

Substituting in the probability of error equation yields

$$P_{\mathrm{e}} = \sum_{a=1}^{N_{\mathrm{C}}}\sum_{j=0}^{M-K}\pi_{a,j}\cdot P_{\mathrm{e}}(a-1). \quad (14)$$

As mentioned earlier, the WDM/OCDM based HOS is presented regardless of the type of the OCDM scheme. Previous studies showed that if the number of active users exceeds a specified threshold N_{A}, the probability of error is increased. N_{A} is slightly smaller than N_{C} and can be obtained considering the probability of error relation and the code parameters including the code length, code weight, and the maximum cross correlation[19,20]. Therefore, the probability of outage P_{out} is defined as the probability that the number of active users in each WDM window exceeds N_A and can be calculated as[20]

$$P_{\mathrm{out}} = P_{\mathrm{r}}(a > N_{\mathrm{A}}) = \sum_{a=N_{\mathrm{A}}+1}^{N_{\mathrm{C}}} P_{\mathrm{A}}(a). \quad (15)$$

The three performance metrics derived above for the proposed HOS have been calculated under different traffic scenarios and network conditions. Our results are plotted in Figs. 5–12. In Fig. 5, the blocking probability P_{B} has been plotted versus the ratio between output and input channels (K/M) at different values of the total offered load ρ. General and expected trends of the curves can be noticed. Of course, P_{B} is increased as the offered load increases. Note that P_{B} in the proposed model of the HOS is slightly greater than its counterpart in the case of accepting only control packets for burst scheduling. This is due to the fact that when a burst is blocked at a switch, the input wavelength carrying the blocked burst will be considered inactive until the end of the burst has arrived at the switch. During the period of time that a burst is being dumped at the switch, the input wavelength is said to be blocked. Therefore, the blocked input wavelength encounters a longer OFF period. In other words, the OFF period is said to be lengthened.

Note that when a circuit request is blocked, there is no dumping, and the circuit is assumed lost. As a consequence, the total offered load (circuits and bursts) arriving at a hybrid optical switch will be considered slightly greater than the total offered load (bursts only) arriving at an OBS core node possesing the same available number of channels. As a result, the P_{B} in this case is slightly greater than that of the previous model. Figure 6 reveals the fact that the primary factor that can relax the P_{B} is increasing the number of channels, not lowering the offered load.

Figure 7 illustrates that the MinF resource allocation

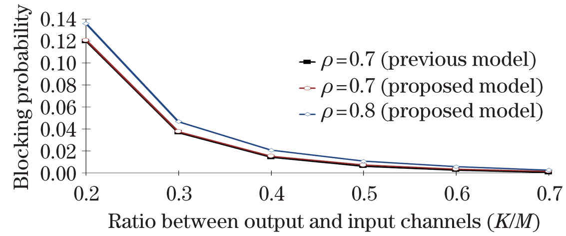

Fig. 5. P_{B} versus K/M for different offered loads.

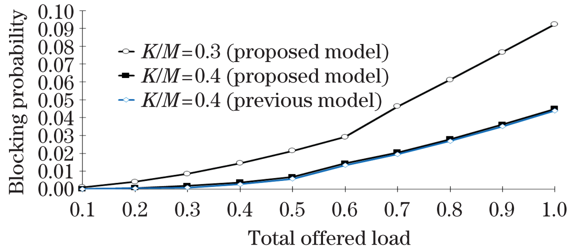

Fig. 6. P_B versus offered load at different K/M.

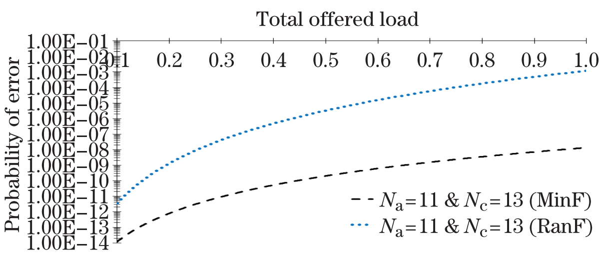

Fig. 7. Comparison of P_e for MinF and RanF resource allocation strategy.

strategy greatly reduce the probability of error than RanF strategy for the same applied code. For the proposed HOS with MinF strategy, the code parameters affect the performance. This fact has been justified by Beyranvand *et al.*[23] for supporting multiservice GMPLS networks. They mentioned that to provide a requested service, the length and the weight of codes are designed based on the service characteristics. In this paper, two codes are used, and they are defined as

1) 1st code: $L = 100$, $w = 10$, $I_C = 2$ this leads to $N_C = 13$.

2) 2nd code: $L = 400$, $w = 18$, $I_C = 2$ this leads to $N_C = 32$.

where L, w, I_C, and N_C denote the code length, code weight, maximum cross correlation, and number of available codes, respectively. It is cleared from Fig. 8 that at the same offered load, the 1st code provides lower probability of error. However, it suffers from higher probability of outage due to its small number of available codes. This is due to the fact that the threshold value (N_a) in the 1st code is smaller than its counterpart in the 2nd code. Therefore, a certain periority may be achieved by assigning the 1st code to higher periority users while the 2nd code to lower periority users.

The probability of error can be reduced by two methods, either by relaxing the offered load or by changing the resource allocation strategy. Relaxing the load is not my concern, instead it depends on the network conditions. Thus, appling MinF instead of RanF greatly solved the probability of error problem, and this can be illustrated in Figs. 9 and 10.

As mentioned earlier, the 1st code provides higher P_{out} due to its small value of N_a. Also, the MinF strategy solved the P_{out} problem since it chooses a WDM window with the minimum number of active users, and assigns one of its free codes. Figs. 11 and 12 verify these conclusions.

In conclusion, a hybrid optical switch is proposed with physical layer of WDM/OCDM. Traffic multiplexing is achieved through this HOS by accepting control packets for both circuit establishment and burst scheduling.

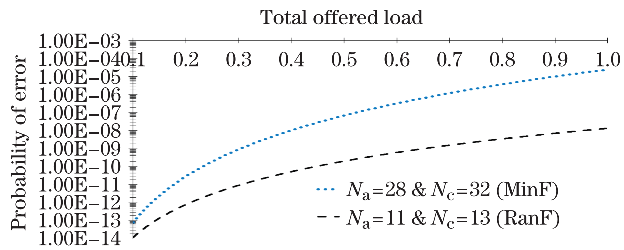

Fig. 8. P_e versus offered load for 2-different codes.

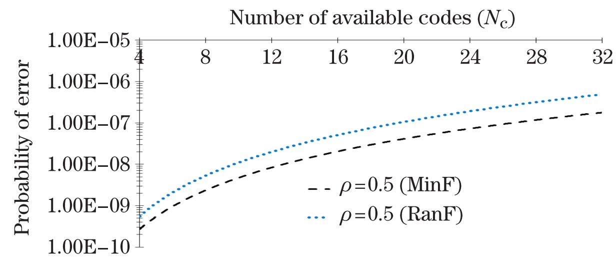

Fig. 9. P_e versus number of available codes at different offered loads.

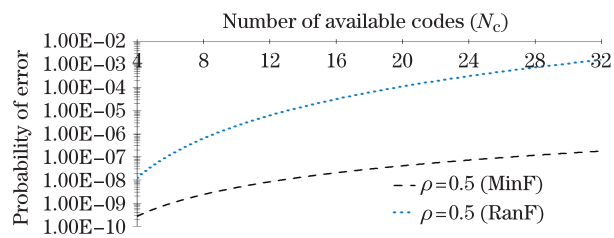

Fig. 10. Comparison of P_e for MinF and RanF resource allocation strategy.

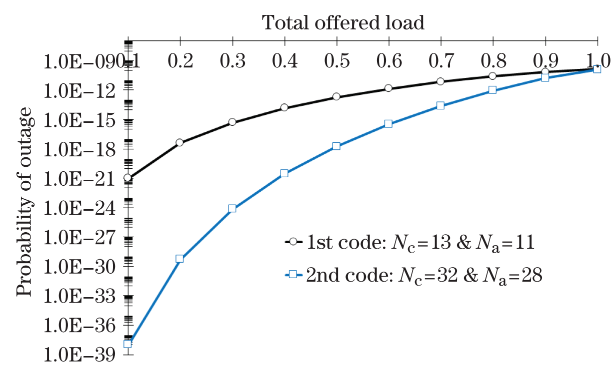

Fig. 11. P_{out} versus offered load for 2-different codes.

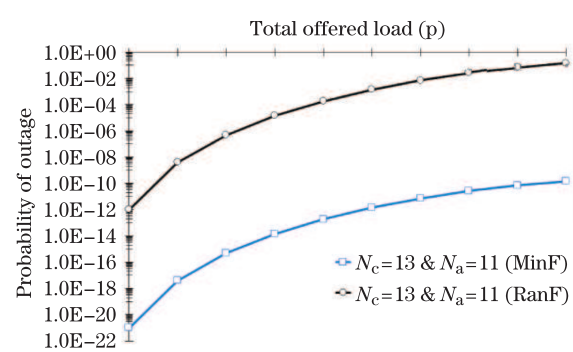

Fig. 12. Comparison of P_{out} for MinF and RanF resource allocation strategy.

Performance metrics for this HOS are blocking probability, probability of error, and probability of outage. Blocking probability is evaluated with no periority given to circuits nor bursts. The probability mass function (pmf) of the number of active users in each WDM window is evaluated based on 2D Markov model using MinF strategy. Probability of error and outage are calculated based on $P_{\mathrm{A}}(a)$. The results reveal that MinF resource allocation strategy greatly reduced P_{e} and P_{out}. Finally, shorter codes provides smaller P_{e} but higher P_{out}.

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