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RESEARCH ARTICLE

Performance analysis of a hybrid OCDMA/WDM system

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Abstract The performance of the hybrid optical code-division multiple-access (OCDMA) and wavelength division multiplexing (WDM) network is analyzed. End-to-end bit error rate (BER) of the network adopting error correction coding is calculated, and the expressions which show spectral efficiency performance, including the effects of polarization mode dispersion (PMD), are derived. The result demonstrates that PMD can decrease spectral efficiency dramatically. Analysis of the blocking performance with and without orthogonal optical codes (OOCs) and wavelength conversion shows that OOC and wavelength can improve the performance of the network. Since the wavelength conversion is much more costly than OOC conversion, a scheme for spare placement wavelength conversion is introduced to balance the cost and performance.

Keywords optical code-division multiple-access (OCDMA), wavelength division multiplexing (WDM), wavelength path, label channel, bit error rate (BER), spectral efficiency, blocking probability

1 Introduction

The optical code-division multiple-access (OCDMA) technique, which allows multiple users to share the same transmission media by assigning different optical codes (OCs) to different users, is an attractive candidate for next generation broadband access networks [1]. Data is encoded into OCs by the OCDMA encoder at the transmitter, and multiple users share the same transmission media by using a power splitter/combiner. At the receiver, the OCDMA decoder recognizes the OCs by performing matched filtering. Since OCDMA network capacity is limited [2] and spectral efficiency is low [3,4], a hybrid OCDMA/WDM network that can support a large number of users and has high spectral efficiency is proposed. The basic architecture of the OCDMA/WDM network is illustrated in Fig.1, where WP means wavelength path; LC means label channel; and w, m means number of waves and labels respectively. In this architecture, OCDMA channels can be overlayed on wavelength division multiplexing (WDM) wavelength paths. On each WDM wavelength path λ_i ($i = 1,2,\ldots,w$), m users can be accommodated by individually assigning each user with a different OC i ($i = 1,2,...,m$). The same code sequence OC i can be reused on all the WDM wavelength paths. The total number of users that can be accommodated in the OCDMA/WDM network becomes $w \times m$, and each user occupies the whole one OOC/wavelength channel.

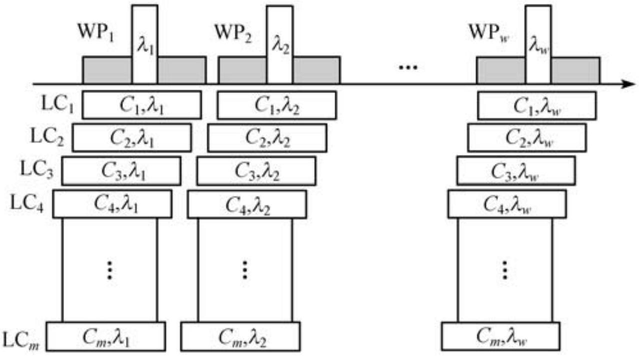

Fig. 1 Architecture of an OCDMA/WDM system (WP: wavelength path; LC: label channel; w: number of waves; m: number of labels)

Many experiments of OCDMA/WDM networks are established [5,6] and high performances are illustrated from the results. In this paper, through mathematical analysis, the performance of the OCDMA/WDM network is derived, and some numerical results are obtained. The paper is organized as follows: in Sect. 2, the performances of an OCDMA/WDM network are analyzed, while numerical results and the corresponding discussion are shown in Sect. 3; Sect. 4 concludes the study.

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2 Performances analysis

2.1 Bit error rate (BER) analysis

In this work, incoherent orthogonal optical codes (OOCs) are adopted due to their technological maturity compared to coherent codes [7]. The total OOCs can be characterized by $(L,\omega,1,1)$, where L and ω are the length and weight, respectively, and the auto-correlation and cross-correlation are 1.

1) BER of a single node

With K denoting the number of active users, the BER is proposed by taking multiple-access interference (MAI) into account:

$$\begin{aligned} B_{\mathrm{BER}} &= P_{\mathrm{r}}(b=0)P_{\mathrm{r}}(Z > T_{\mathrm{h}}|b=0) \\ &\quad + P_{\mathrm{r}}(b=1)P_{\mathrm{r}}(Z < T_{\mathrm{h}}|b=1), \end{aligned} \tag{1}$$

where T_{h} is threshold for the decision; terms $P_{\mathrm{r}}(b=0)$ and $P_{\mathrm{r}}(b=1)$ are the probabilities for bit b is “0” and “1” respectively; and $P_{\mathrm{r}}(b=0) = P_{\mathrm{r}}(b=1) = 1/2$. The second term of Eq. (1) can be considered as 0 for $0 < T_{\mathrm{h}} < \omega$ because the output signal with autocorrelation is always not smaller than ω. Hence, Eq. (1) can be simplified as

$$B_{\mathrm{BER}}(L,K) = \frac{1}{2}\sum_{i=T_{\mathrm{h}}}^{K-1} C_{K-1}^{i}\left(\frac{\omega^2}{2L}\right)^{i}\left(1-\frac{\omega^2}{2L}\right)^{K-1-i},$$

where K is the number of active users. From Eq. (1), it can be seen that B_{BER} is influenced by T_{h}, even with the same number of active users. In Ref. [8], a variable optimum optical threshold T_{h} can help improve bit error performance. However, for simplicity the T_{h} is set to the value of ω.

2) BER using error correction coding

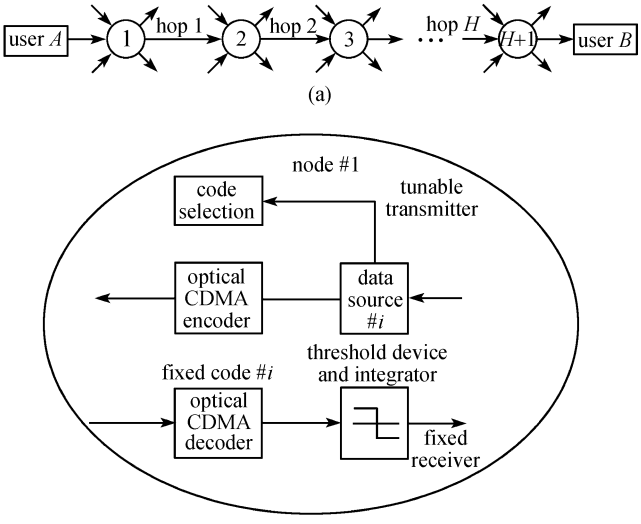
Error correction coding is shown to be useful for improving the performance of an OCDMA system using incoherent optical signal processing [9]. An (n,k,t) Bose-Chaudhuri-Hocquenghem (BCH) code with length n and information-bit length k can correct up to t word errors. BER with BCH error correction coding is derived as

$$B_{\mathrm{BER\ BCH}} \leqslant \sum_{i=t+1}^{n} \frac{i+t}{n} C_n^i B_{\mathrm{BER}}^i (1-B_{\mathrm{BER}})^{n-i}.$$

3) BER of end-to-end

In a practical optical system, we pay more attention to the BER from the source node to the destination node. As shown in Fig. 2, data is successfully received only if it is transmitted successfully on each hop, in which requested links are labeled, and the other links are interfering links. $B_{\mathrm{BER}\ i}$ is the B_{BER} of the ith node and $B_{\mathrm{BER}\ i} \ll 1$, $1-B_{\mathrm{BER}\ i}$ is the right probability of the ith node. Thus, the high-level of BER can be ignored, and the expression of BER of H hops is derived as

$$\begin{aligned} B_{\mathrm{BER}} &= 1-\prod_{i=1}^{H}(1-B_{\mathrm{BER}\ i}) \\ &= 1-\left(1-\sum_{i=1}^{H} B_{\mathrm{BER}\ i} + \sum_{i=1}^{H-1}\sum_{j=i+1}^{H} B_{\mathrm{BER}\ i}B_{\mathrm{BER}\ j} + \cdots\right) \\ &= 1-\left(1-\sum_{i=1}^{H} B_{\mathrm{BER}\ i}\right) \\ &= \sum_{i=1}^{H} B_{\mathrm{BER}\ i}. \end{aligned} \tag{2}$$



(a)

(b)

Fig. 2 (a) H hop requests; (b) structure of the node

From Eq. (2), it can be seen that the BER of end-to-end is influenced by the BER of single node. Therefore, if the BER is very large in one single node, the whole performance of the network is poor.

2.2 Spectral efficiency analysis

Because bandwidth is a scarce resource in wireless communication systems, spectral efficiency is an important performance measure. Although bandwidth is abundant in an optical domain, the spectral impacts per-user communication rate, the number of users allowed on the network and the corresponding cost of the system. We define the spectral efficiency η of an OCDMA/WDM system as the data rate per channel bandwidth unit for a specified average transmitted power and fixed BER value:

$$\eta = \frac{N_{\mathrm{BER}}R_{\mathrm{b}}}{w\Delta f}, \tag{3}$$

where N_{BER} is the number of simultaneous users with a fixed BER in the network; R_{b} is the bit rate per user; Δf is the bandwidth of each wavelength path; and w is the number of wavelength paths. Given the same chip rate and using error correction coding, the bit rate of the user should be decreased, i.e., $R_{\mathrm{BCH}} = (k/n)R_{\mathrm{b}}$. Thus, the spectral efficiency of the system can be derived by adopting the error correction coding:

$$\eta_{\mathrm{BCH}} = \frac{N_{\mathrm{BCH}}R_{\mathrm{BCH}}}{w\Delta f} = \frac{kN_{\mathrm{BCH}}R_{\mathrm{b}}}{nw\Delta f},$$

where R_{BCH} is the new bit rate and N_{BCH} is the number of simultaneous users with a fixed BER in the system.

In an OCDMA/WDM system, due to fiber dispersion which causes the temporal spreading of chip pluses, for a given fiber link distance L_{T}, there is an upper limit on the chip-rate distance product, which is $LL_{\mathrm{T}}R_{\mathrm{b}}$ [10], where L is the length of the code. Of particular concern is polarization mode dispersion (PMD), which is prevalent in the majority of current fiber plants and places an upper limit on code length, which in turn limits the number of distinct codes. The main restriction of PMD shows that the average differential group delay of two orthogonal polarization states should be less than one fraction of bit duration, $T = 1/R_{\mathrm{b}}$, where R_{b} is the bit rate of the system. The product of chip-rate and distance is derived in Ref. [10]:

$$R_{\mathrm{b}}L\sqrt{D_{\mathrm{PMD}}^{2}L_{\mathrm{T}}} < \alpha, \tag{4}$$

where L is the length of OOC; D_{PMD} is the fiber PMD parameter measured in $\mathrm{ps\cdot km^{-1/2}}$; and L_{T} is the span length measured in km. A typical value of α is 0.1 [10]. The PMD parameter for typical fibers ranges from 0.2 to $0.5\ \mathrm{ps\cdot km^{-1/2}}$. From Eqs. (3) and (4), we can evaluate the effects to the spectral efficiency by the PMD.

2.3 Blocking probability analysis

In this section, a model for evaluating the blocking probability of OCDMA/WDM systems is proposed. As shown in Figs. 3 and 4, several kinds of routings are illustrated. We obtain the blocking probability of the system with and without OOC and wavelength conversions. The following assumptions are used:

1) there are w wavelength paths per link, and each wavelength path can support m label channels, i.e., there are $w \times m$ OOC/wavelength paths;

2) each connection occupies an entire OOC/wavelength channel;

3) it can be assumed that a connection between the source node and the destination node always chooses the shortest path; dynamic routing provides better performance but is too complicated;

4) if a connection is blocked, it is immediately discarded;

5) connection arrivals have the Poisson distribution with the average λ;

6) there are H hops between the source node and the destination node.

In OCDMA/WDM systems there are two approaches to the label channel and wavelength path assignments: with and without the OOC and wavelength conversions. Let $p(k)$ be the probability that k OOC/wavelength channels are used on a link, with previous assumption,

$$p(k) = \frac{\lambda^k}{k!}\Bigg/\sum_{t=1}^{wm}\frac{\lambda^t}{t!}. \tag{5}$$

For a convention wavelength routing network, Barry's formula provides equations to study the qualitative behavior of the networks by making a simplistic traffic assumption [11]. In the formula, a link without wavelength conversion is decomposed into fixed-wavelength paths whose blocking probabilities are independent. The end-to-end blocking probability of the link is obtained by calculating the blocking probability of each wavelength path. In the following, we will extend Barry's analysis to investigate blocking performance of the OCDMA/WDM network proposed.

1) Without OOC and wavelength conversions (case (A) in Fig. 3)

We first consider the blocking probability in the case where no OOC and wavelength conversion is taking place. The link is decomposed into w fixed-wavelength paths, and each wavelength path can support m fixed-OOC channels. In such cases, a request for connection between source and

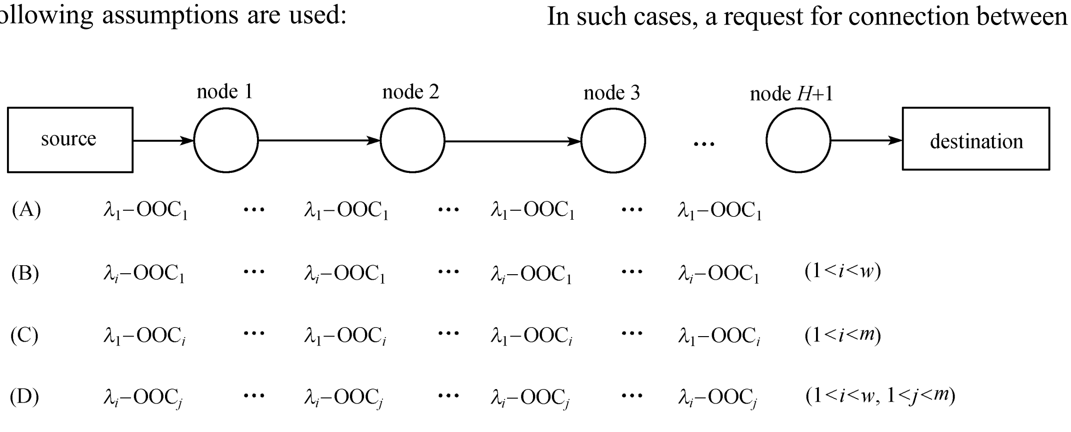


Fig. 3 Routing of an OCDMA/WDM system

destination will be blocked if there is no same OOC/wavelength channel, which is available on every hop between them. Let ρ be the probability that OOC/wavelength channel λ_1–OOC_1 is used on a hop, and the probability that the request adopting λ_1–OOC_1 is blocked is $1-(1-\rho)^H$. The probability that a wavelength path is blocked is $1-(1-\rho)^{Hm}$. Thus, the probability of the system without OOC and wavelength conversion is

$$P_a = 1-(1-\rho)^{Hmw},$$

where $\rho = \sum_{i=1}^{m} \frac{i}{m} p(i)$, $p(i)$ can be derived from Eq. (5).

2) Only with wavelength conversions (case (B) in Fig. 3)

Now consider a network only with wavelength conversion. In this case all the nodes are equipped with wavelength conversion capability. The link is decomposed into m fixed-OOC channels, and the λ_i–OOC_1 $(1<i<w)$ channel is blocked on a hop only when all the OOC_1/λ_i channels are used. There are w independent channels with uniform link load for each hop. Given the probability that all w channels are used is $p(w)$ which can be calculated from Eq. (5), then $P_b(\mathrm{OOC}_1) = (1-p(w))^H$. The blocking probability of the network only with wavelength conversion is thus derived as

$$P_b = (1-(1-p(w))^H)^m.$$

3) Only with OOC conversions (case (C) in Fig. 3)

Since each hop has no ability for wavelength conversion but has OOC conversion capability, the establishment of channels should comply with the fixed wavelength constraint. The link is decomposed into w fixed-wavelength paths, where each wavelength path can support m independent OOC channels with uniform link load. Let $p(m)$ be the probability that all the m OOC channels are used and can be calculated from Eq. (5). The blocking probability of the network only with OOC conversion is thus

$$P_c = (1-(1-p(m))^H)^w. \tag{6}$$

4) With OOC and wavelength conversions (case (D) in Fig. 3)

In this case where all nodes are equipped with full conversion capability, there are mw independent OOC/wavelength channels for each hop. Referring to the derivation from Ref. [11], the blocking probability of the network can be approximated as

$$P_d = (1-p(mw))^H,$$

$p(mw)$ can be derived from Eq. (5).

5) Spare placement of wavelength conversions

Since wavelength conversion is much more costly than OOC conversion, it is worthwhile to investigate how to avoid wavelength conversion in the network and find a balance between cost and performance. In Ref. [12], the uniform placement is a proven optimal scheme in a conventional wavelength routing network and sparely placed wavelength converters. As shown in Fig. 4, the wavelength conversions separate the whole link into K sub-links, and each sub-link is equivalent to the link in case (C) where there was OOC conversion only. The blocking probability of the kth sub-link can be derived from Eq. (6). The blocking probability of the whole link under the scenario of uniform placement is

$$P_e = 1-(1-(1-(1-p(m))^w)^l)^K,$$

where l is the number of hops in a sub-link, which is equal to H/K.

3 Numerical results

Numerical results generated from the above equations are shown in this section. Figure 5(a) shows that BER increases dramatically by increasing the active number, while the BCH code can improve the performance of the network. The BER decreases significantly in adopting the BCH code when the number of active users is small. Figure 5(b) shows the end-to-end BER of H hops. The BER changes slowly by increasing the hop number, increasing from 10^{-9} to 10^{-8} when the hop number increases from 1 to 20.

In Fig. 6, the spectral efficiency of the network is exhibited, and the fixed BER is 10^{-9}. Figure 6(a) illustrates the spectral efficiency when considering the effect of the PMD and adopting the BCH code. The spectral efficiency is 1.3×10^{-2} bit/s/Hz without BCH and PMD, decreases to 1.0×10^{-2} bit/s/Hz when considering the PMD, and then can be increased to 3.0×10^{-2} bit/s/Hz in adopting the BCH

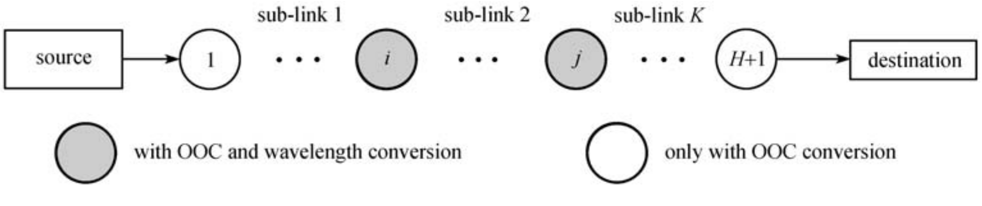
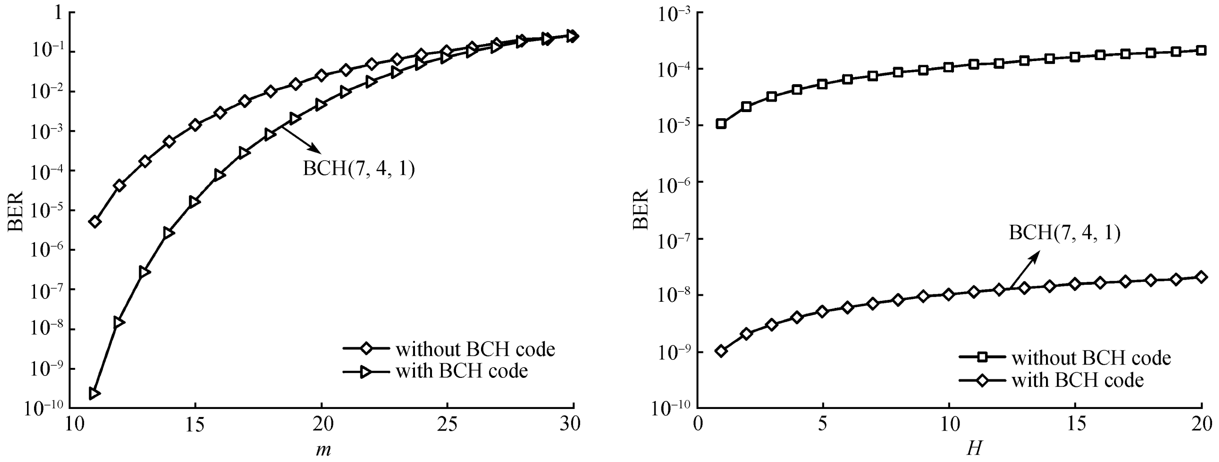
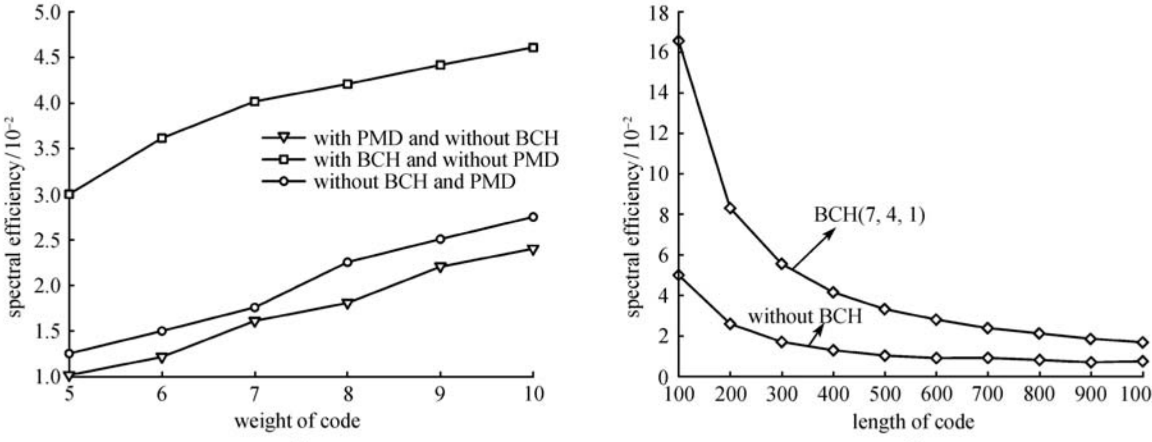


Fig. 4 Spare placement of wavelength conversion



(a) (b)

Fig. 5 BER performance of the system. (a) BER versus number of active users (L = 158, ω = 8); (b) BER versus number of hops (L = 158, ω = 8, m = 10)



(a) (b)

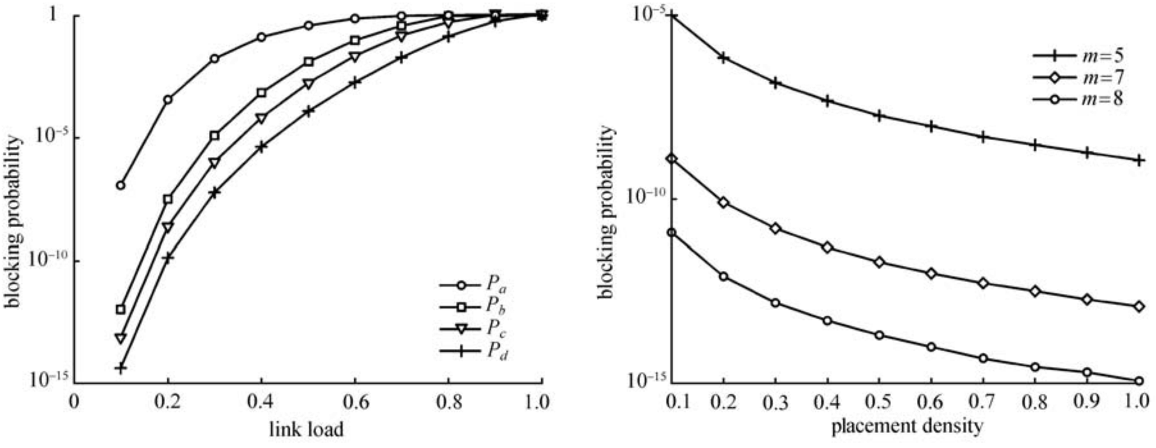
Fig. 6 Spectral efficiency of the system. (a) Spectral efficiency versus weight of the code; (b) spectral efficiency versus length of the code (w = 30, ω = 5)

code. Parameters used here are $\alpha = 0.1$, $R_b = 2.5$ Gbit/s, w = 30, $D_{\text{PMD}} = 0.2\,\text{ps}\cdot\text{km}^{-1/2}$, L_T = 5 km. Figure 6(b) shows the spectral efficiency versus the code length. The coefficient of spread increases by increasing the code length and correspondingly decreasing spectral efficiency. The spectral efficiency can be increased by using BCH code.

Figure 7(a) shows the blocking probability with different conditions. This probability is much higher without OOC and wavelength conversion. Parameters used here are H = 14, w = 3, m = 5. From Fig. 7(b), the impact of the number of wavelengths on network performance can be seen. For example, the blocking probability decreases from 10^{-11} for placement density of 0.1 to 10^{-14} for the placement density of 0.5.

4 Conclusion

In this paper, several performances of the OCDMA/WDM network are analyzed. Expression of the BER is derived by adopting the BCH code, and then evaluating the end-to-end BER of the network. Results show that the change slowly occurs by increasing the hop, and the BCH code can improve the performance of the network. The impact of PMD is considered when evaluating the spectral efficiency and the PMD can decrease the spectral efficiency dramatically. Finally, the model for evaluating blocking probability is proposed, and blocking probability of the network with and without the OOC and wavelength conversion is discussed. A scheme to spare placement of



(a) (b)

Fig. 7 Blocking probability of the system. (a) Blocking probability versus link load with different conditions; (b) blocking probability versus placement density (H = 10, w = 5)

wavelength conversion is then discussed, which can balance the cost and performance of the network.

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