Performance Improvement by Code Conversion in a Reconfigurable Optical Code/Wavelength Routing Network

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ABSTRACT

Recent advances in optical devices greatly enhance the feasibility of optical code-division multiplexing/wavelength-division multiplexing (CDM/WDM) network. In this paper, the performance in blocking probability in a two-dimension code/wavelength routing network is investigated. Facilitated by the optical code and wavelength conversion, the capability in reconfigurability, restoration and protection of the optical layer is enhanced. The network blocking performances under various conversion capabilities are investigated and the blocking probabilities are given in closed-form expressions. Under certain conditions, the analysis of the two-dimension routing network can be extended to N-dimension routing network by iterative decomposition procedure. Numerical results are obtained to show the performance improvement from the optical code conversion in terms of code conversion gain. With wavelength conversion provided in the network, the addition of the code conversion achieves a conversion gain as high as 10^4 even when the code conversion is provided with a low placement density of 0.2.

Key words: optical correlated code, code/wavelength routing, wavelength conversion, code conversion, full-permutation.

1. INTRODUCTION

Wavelength Division Multiplexing (WDM) network is the most promising solution to the explosively growing bandwidth demand in today's internetworking. Wavelength routing is one of the major mechanisms for WDM transport networks. Wavelength routing overcomes the scalability constrains through wavelength reuse, wavelength conversion and optical switching when the network extends to wide area. Therefore it is an important mechanism for optical transport networks.

In a wavelength routing network carrying circuit switched traffic, the whole bandwidth of a wavelength on each link is dedicated to a source-destination pair to carry the traffic between them. Although one wavelength can offer nearly the peak electrical transmission speed, without efficient bandwidth allocation, the low data-rate traffic will also take up the entire bandwidth of a wavelength and induce a very luxurious consumption of the resource. Moreover, limited number of wavelengths, which is around several tens per fiber nowadays, reduces the flexibility in bandwidth allocation and limits

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the bandwidth granularity for heterogeneous services in Internet traffic.

In addition to WDM, other all-optical multiplexing mechanisms, such as optical time-division multiplexing (OTDM), optical code-division multiplexing (OCDM), and polarization-division multiplexing (PDM), allow multiple subscribers share a common bandwidth resource. Recently, OCDM has been extensively investigated. Though it is not as mature and popular as its counter part in mobile communication, recent advances in photonic devices, such as planar lightwave circuit (PLC) and super structure fiber Bragg grating (SS-FBG), have greatly enhance the feasibility of OCDM. In an optical code-domain multiplexing access (OCDMA) network, the optical correlated codes (OCC) are used as symbols of the desired destination addresses. When tunable optical encoders and decoders are employed, one subscriber can communicate with any other user in the network. Previous works include the experiment demonstrations of OCDM transmission systems as well as OCDM network using optical code conversion [1][2]. More recently, the optical correlated codes are introduced as labels in a photonic multiple protocol label switching network (OMPLS), in order to simplify and speed up the processing in the Label Switched Router (LSR) [3][4].

Implementing the multiplexing in the optical layer, OCDM can further enhance bandwidth granularity of the WDM transport network and gives rise to the OCDM/WDM hybrid network. It is shown that, the spectrum efficiency of the OCDM/WDM network could be twice as much of that with WDM only [2]. Bandwidth on one wavelength can be divided into small fractions labeled by optical codes, and assigned to different connections. In this way, provisioning fractional wavelength capacity is achieved by the marriage of OCDM with WDM. Different from the wavelength routing in a conventional WDM network, there are two dimensions of OCC and wavelength used for optical routing. It is called code/wavelength routing network.

In this paper, the main work will focus on the blocking performance of a code/wavelength routing network. Blocking performance and conversion gain are investigated with uniform traffic models. Closed-form expressions are derived to show the improvement from the reconfiguration capability on the code dimension. The extension of the analysis to N-dimension will be described. This paper is structured as the following. The reconfiguration capability arising from optical conversion is discussed in section 2. Section 3 presents the blocking performance of the path with various conversion capabilities in closed-form expressions. Numerical results showing the performance improvements from code conversion are depicted in Section 4. Finally the paper is concluded in Section 5.

2. RECONFIGURATION CAPABILITY IN A CODE/WAVELENGTH ROUTING NETWORK

For an optical network, one of the latest research thrusts is to enhance the optical layer control by increasing the reconfiguration capability of the network elements. In a simple wavelength routing network, wavelength converter is one of the most important reconfigurable elements. It allows optical input signals on one wavelength to be converted to another wavelength on the output link. It is obviously that with wavelength conversion, the routing nodes have more freedom when transfer the data, and the network performance can be improved [5]. The wavelength routing networks with wavelength conversion have been extensively studied through many different models [5][6][7]. In particular, optical networks based on sparse wavelength converters placement and limited conversion range have also been analyzed because of the high cost of the wavelength converter and its impairment to the transmission [8][9].

In an OCDM/WDM network, to enhance the reconfiguration capability of the optical layer, wavelength conversion (WC) and optical code conversion (CC) can both be utilized. Optical code conversion is used to translate input signals from one code channel to another code channel. Possible configurations are proposed recently in [2][10].

Consider a network with single fiber for each link. Let H denotes the number of hops along a path, N denotes the number of wavelengths per fiber and M represents the number of code channels per wavelength. Therefore all together $M \times N$ channels exist on a link. Every code/wavelength channel could be uniquely represented by a set of (h, n, m), representing its indices of the hop, the wavelength and the code, respectively, where $1 \le h \le H$, $1 \le n \le N$, $1 \le m \le M$. The four types of routing nodes in a code/wavelength routing network can be described by their transfer functions T as below:

(1). The non-convertible routing node (NR):

The node is only used for interconnecting fiber links and does not have any optical conversion capability. The input optical signal can only be put on the same code/wavelength channel on the output fiber. As it is shown in Fig.1(a), the input channel is (h, n, m), and the possible channel of the output link is represent by the hatched square in the link of h+1. The transfer function of such a node can be described as $T_o(h,n,m) = (h+1,n,m)$.

(2). The code routing node (CR):

This node could implement code conversion for the code channels, keeping the wavelength of the input signal unchanged. Shown in Fig.1(b), the input signal on (h, n, m) can be converted to any code channel on the wavelength n. The transfer function can be represented as $T_C(h,n,m) = (h+1,n,m')$ where $1 \le m' \le M$.

(3). The wavelength routing node (WR):

This node can implement wavelength conversion as shown in Fig.1(c), the input signal on (h, n, m) can appear at any wavelength channel on the code m. And the transfer function is $T_W(h,n,m) = (h+1,n',m)$ where $1 \le n' \le N$.

(4). The full-permutation node (FR):

The node has integrated functions of a wavelength and code conversion, which can route the input signal to any code/wavelength channel on the output port. As shown in Fig.1(d), its transfer function is $T_F(h,n,m) = (h+1,n',m')$ where $1 \le n' \le N$ and $1 \le m' \le M$.

These four kinds of the routing nodes give rise to different reconfigure capability in the optical network, which will benefit the network in the aspects of rerouting, optical restoration and protection. Employing WC and CC in the network, a much flexible optical routing is achieved because it eliminates the constraint of routing on the fixed wavelength and code channel.

3. ANALYTIC MODELS

In this section, the blocking probability in an optical code/wavelength routing network carrying circuit switched traffic will be discussed. As stated before, in this paper the network under investigation consists of single-fiber links with N wavelengths per fiber and M code channels per wavelength. Shown in Fig.2(a), user A requests for a session with user B through the path of H hops. In the following, the blocking probabilities of the session with different conversion capabilities on the paths are investigated. For simplicity, we assume the uniform link loads on each code/wavelength channel.

(1). Path with no optical conversions

We first consider the case that there is no optical conversion allowed on the path, as shown in Fig.2(a). The establishment of the connections should obey the rule of code/wavelength continuity. That means any neighboring connections should employ the same code and wavelength channel in order to setup the lightpath. Similar to the conventional fixed wavelength routing network, the session will be blocked if all the NxM code/wavelength continuous lightpaths are blocked. Assume each code/wavelength channel has a load of ρ, referring to [5], the blocking probability of the path denoted by P_{B0} is:

$$P_{B0}(H,N,M) = (1-(1-\rho)^{H})^{N\times M} \quad (1)$$

(2). Path with CRs only

For a network deployed with code converters only, wavelength conversion still cannot be performed. Therefore, the continuity of wavelength constrain should be obeyed during connections setup. A path with only code conversion is shown in Fig.2(b). Here, we regard all the code channels on a wavelength in one hop as a trunk. A certain trunk n is said busy if all the code channels in it are occupied, otherwise it is free. We define the successive trunk sequence between the source and destination nodes as trunk path. The trunk path is said successful if the end-to-end connections can be set up within it, or it is regarded as blocked. It is clear that, between the source and destination nodes, the number of fixed wavelength trunk paths are N, which is equal to the number of wavelengths. These N wavelength trunk paths are independent. On each trunk there are M code channels which are the code number per wavelength. Therefore, the blocking probability of an end-to-end path with H hops could be derived as:

$$\begin{aligned} P_{BC}(H,N,M) &= P\{\text{all } N \text{ wavelength Continuous trunk path are blocked}\} \\ &= \prod_{n=1}^{N} P\{\text{the trunk path } n \text{ is blocked}\} \end{aligned}$$

Note that the blocking probability of each trunk path n is equal to the blocking probability of the conventional wavelength routing network with wavelength converters as derived in [5]. Therefore, the blocking probability of a session when only CRs in the path can be expressed as:

$$P_{BC} = (H,N,M) = \prod_{n=1}^{N}(1-(1-\rho^{M})^{H}) = (1-(1-\rho^{M})^{H})^{N} \quad (2)$$

Thus we show that for this case, the original two-dimensional (code/wavelength) routing problem can be decomposed to one-dimensional routing problem. Similar results can be obtained for the case when there is only WR only.

(3). Path with FRs only

For the case that all the nodes on the path are equipped with full-permutation, as shown in Fig.2 (c), blocking would occur when any one of the H hops is blocked. In this case, we can consider the two-dimensional channels (N wavelength and M code) as one-dimensional channels with channel number NxM. Thus from [5], the blocking probability can be derived as:

$$P_{BF} = (H,N,M) = 1-(1-\rho^{N\times M})^{H} \quad (3)$$

Again, we are able to covert the two-dimensional routing problem to one-dimensional problem for this case.

(4). Path with sparsely placed FRs only

The converter is expensive and therefore it is possible that only some nodes will be equipped with it. When full permutation is performed on some nodes while other nodes have no conversion capability, as shown in Fig.2(d), the FRs will cut the path into K sub-path whose blocking probabilities are independent [9]. Within each sub-path, no conversion can be provided, which is exactly the case discussed in (1). The blocking probability can be derived from the equation for conventional wavelength routing network with sparsely placement of wavelength converters. Referring to [9], the uniformly placement is a proved optimal scheme in a simple wavelength routing network under uniform link load. Under this scenario, according to the derivation above, the blocking probability can be expressed as:

$$P_{BSF}(H,N,M)=1-\prod_{k=1}^{K}P\{S^k=1\}=1-(1-(1-(1-\rho)^L)^{N\times M})^K \quad (4)$$

where K is the number of sub-path, L is the average number of hops in a sub-path and $P\{S^k=1\}$ represents the success probability of the sub-path k. It must be noted that the expression (4) is exact only if $K\,|\,H$, otherwise, the above equation is the lower bound of the actual blocking probability [9].

(5). Path with sparsely placed CRs only

In this part we discuss the case that only code conversion is available and the code converters are sparsely placed as shown in Fig.2 (e). We investigate how the number of code converters affects the blocking probability of the path. Similar to the previous part, because there is no wavelength conversion performed, the wavelength continuity constrain is required, and there should be at least one fixed wavelength trunk path can be established in order to set up a successful end-to-end connection. Similar to the discussion in (2), there are N independent and wavelength-continuous trunk paths. Each trunk path is equivalent to one-dimension routing path. Note that each trunk path is cut into K sub-path by the CRs and it is equivalent to the conventional wavelength routing network with sparsely placed wavelength converters. From [9], the probability that a trunk path n succeeds is:

$$P\{S_n=1\}=(1-(1-(1-\rho)^L)^M)^K$$

For a session request, blocking occurs when all the N trunk paths are blocked. In this way, the blocking probability of the path under the scenario of uniform CRs placement is derived as:

$$P_{BSC}(H,N,M)=\prod_{n=1}^{N}(1-P\{S_n=1\})=(1-(1-(1-(1-\rho)^L)^M)^K)^N \quad (5)$$

Therefore, the problem of two-dimension routing with sparsely conversion on one dimension is simplified into one dimension routing problem. Similarly we can obtain the result for path with sparsely placed WR only.

(6). Path with CRs and FRs

Another case that can leads to closed-form solutions is a path with CRs and FRs as shown in Fig.2(f). The full-permutation nodes will cut the path into K sub-segments that are independent as discussed above. Within each sub-path, there is no wavelength conversion permitted, and it is similar to the case discussed in (2). The blocking probability of the kth sub-path can be derived from equation (2):

$$P\{S^k=0\}=(1-(1-\rho^M)^L)^N$$

If the FRs are uniformly placed, the blocking probability of the path is derived as:

$$P_{BCF}(H,N,M)=1-\prod_{k=1}^{K}(1-P\{S^k=0\})=1-(1-(1-(1-\rho^M)^L)^N)^K \quad (6)$$

It is clear that this case of two-dimension routing is decomposed into one dimension routing case to obtain the analytical results. Again we can obtain similar closed-form results for path with WRs and FRs.

In this section, the blocking performance in a code/wavelength routing network with different conversion capability has been investigated to obtain closed-form analytical results. We found that it is possible to obtain closed-form expressions of the end-to-end blocking probability in a two-dimension routing path, by decomposing the two-dimension routing case into single-dimension one. The decomposing principles can be extended to N-dimension routing path (channels are located on N different and independent dimensions) to achieve closed-form expressions for end to end blocking probability.

The goal is to take apart an N-dimension case down to a lower order iteratively until it becomes a one-dimensional problem. In addition, the problem can also be decomposed in spatial domain by dividing the path into several independent sub-blocks. The key issue in the decomposition of channel and spatial domain is to find the independent condition such that the joint distribution can be separated into product terms. The generalization of the decomposition algorithm will be presented in the conference.

4. NUMERICAL RESULTS

From to the derivation above, some numerical results are shown to illustrate the blocking probabilities and code conversion gains under various converter configurations. The improvement of the addition of code-dimension in channel is demonstrated.

Fig.3 shows the blocking probability of a 20-hop path with different number of wavelengths and OCC channels. The total number of channels on a link is fixed at 16. From the graph, it is shown that the blocking probability is the highest when neither conversion is performed, no matter what the individual values of M and N are. With full-permutation performed, the lowest blocking probability is achieved as expected. It is also found that with the aid of code conversion, the blocking performance is improved significantly with the increase of the OCC number. Therefore, we come to the conclusion that when a large set of OCC codes are employed, code conversion will bring significant improvement to the proposed code/wavelength routing network.

Fig.4 demonstrates the blocking probability of a 20-hop path with different placement density of code converters. The ratio of the number of CRs to the total number of nodes is defined as the code converter placement density, represented by q. It is well understood that when all the nodes along the path are CRs, the placement density q is 1. While all the nodes along the path are NRs, q is 0. Otherwise, the q value is between 0 and 1. From this graph, it is quite clear that, higher placement density provides lower blocking probability.

For the case discussed in (5) in section 3, Fig.5 shows the conversion gains with different number of code converters along the path under different link load ρ. Code conversion gain G is defined as $G = \frac{P_{BC}(q)}{P_{BC}(0)}$ where $0 \le q \le 1$. G is investigated for different numbers of code converters used. From Fig.5, we can not only find the code conversion gain increases with the increase of the code converters' number, but also the most significant improvement occurs at $\rho=0.1$. We draw the conclusion that code conversion achieves higher conversion gain at the links with lower load.

The code conversion gain on the path with different code number and wavelength number is demonstrated in Fig.6 when the code converters are uniformly and sparsely placed along the path (corresponding to the case (5) in section 3). In the simulation, although different M and N are used, the total number of channels on a link is fixed at 16. The highest conversion gain occurs when code number M is the biggest, as expected. A high conversion gain, 10^2, can be achieved when M=8 for a placement density of 0.6 (12 CRs on 20 nodes) at the link load of $\rho = 0.4$. Conclusion can be drawn that in the proposed code/wavelength routing network, even when code converters are sparsely placed, they would make significant contribution if a large set of codes is employed.

As shown in Fig. 2(g), in this case, code conversion is provided on the path already having WRs in order to see the code conversion gain under this scenario. The combination of the code and wavelength converter gives rise to the FR. The code conversion gain here is the improvement of blocking probability compared with the case when the path is equipped with WRs only. The numerical result shown in Fig 7 demonstrates that, when code conversion added on four nodes uniformly, a significant gain of 10^4 is achieved.

5. CONCLUSION

In this paper, the performance in blocking probability of optical code/wavelength routing network is investigated. The blocking performance arising from the limited conversion capability in the intermediate nodes of the path is analyzed through uniform traffic model. By the mathematical analysis, closed-form expressions of the blocking probabilities are derived for various cases. It is possible to extend the analysis method to N-dimension routing problems. The numerical results demonstrate the improvement from the code conversion on the network. For optical code/wavelength routing network with a small number of wavelengths but a relatively large number of optical codes, code conversion will make significant performance improvements. When code converters are sparsely placed on a path with a placement density of 0.6 and the total number of channels on a link is fixed of 16, a significant conversion gain of 10^2 is obtained when M equals 8 at the link load of 0.4. With wavelength conversion provided in the network, the addition of the code conversion achieves a conversion gain as high as 10^4 even when the code conversion is provided with a low placement density of 0.2. Thus, the code conversion could help achieve a higher throughput and an efficient utilization of the proposed code/wavelength routing network.

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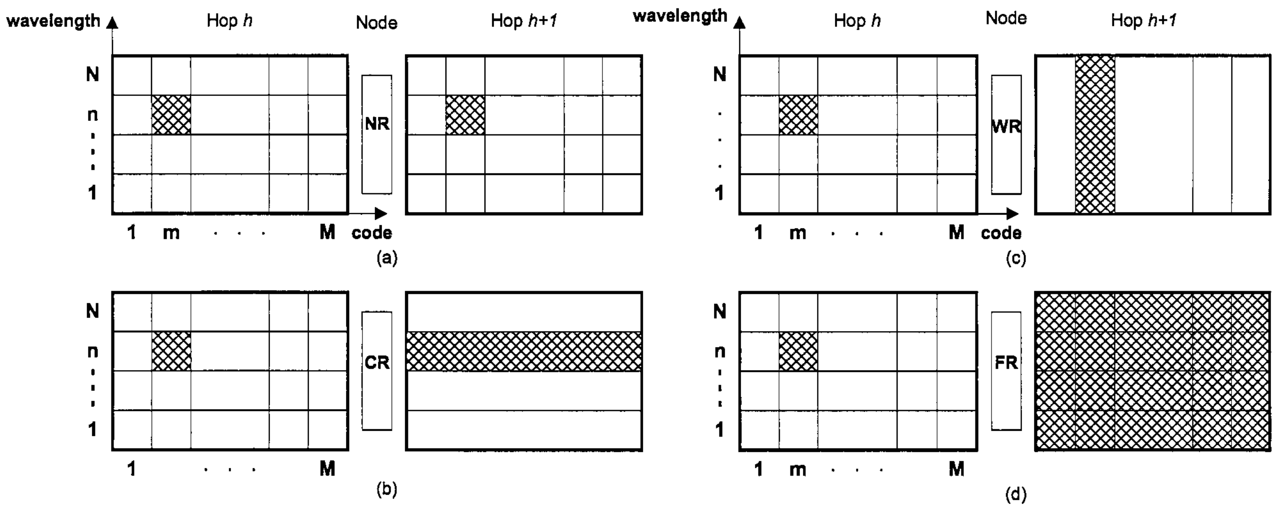

Fig.1 Possible channels for conversion to establish connections on the adjacent hops in a code/wavelength routing network

(a). without conversion capability at the node (c). with wavelength conversion at the node

(b). with code conversion at the node (d). with full-permutation at the node

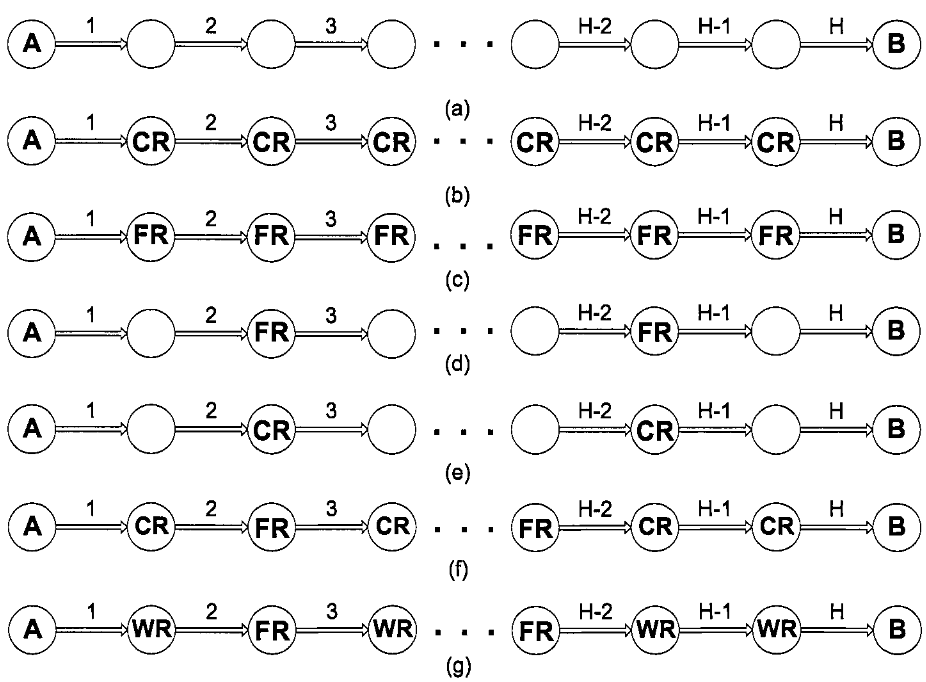

Fig.2 The paths with different reconfiguration capabilities

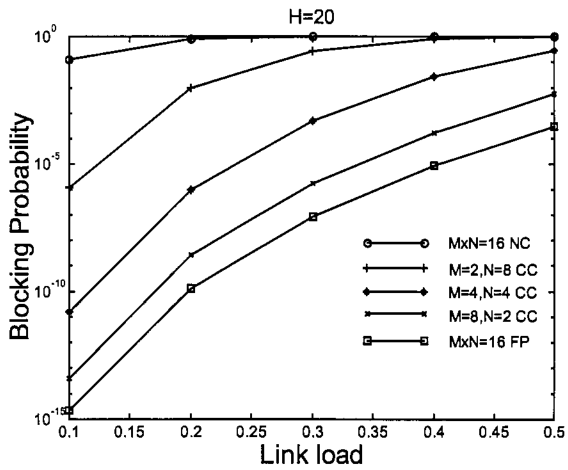

Fig.3 The Blocking Probability versus the link loads ρ with different OCC number M and wavelength number N. NC: no conversion, CC: code conversion FP: full-permutation.

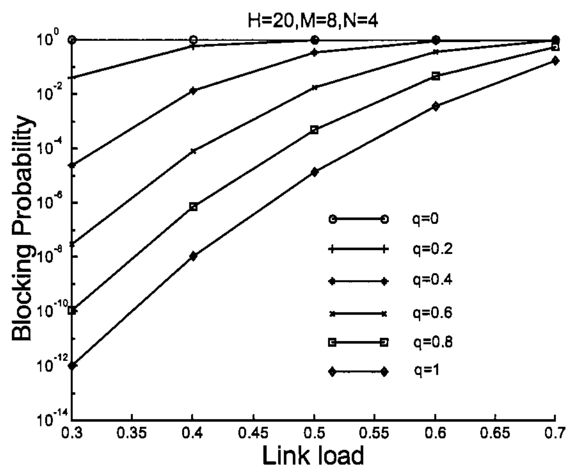

Fig.4 The Blocking Probability versus the link loads ρ with different code converters placement density q at M=8 N=4.

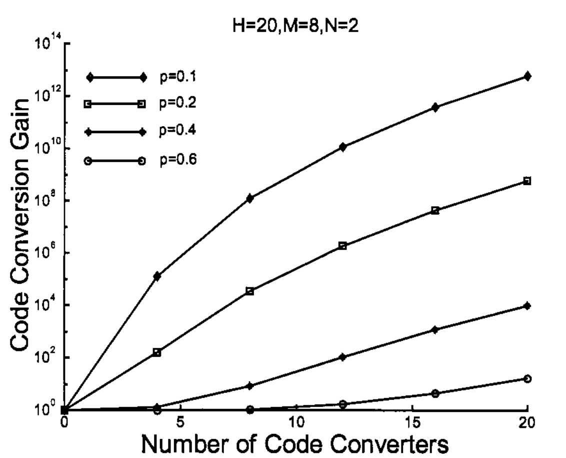

Fig.5 The code conversion gain versus the number of code converters along the path with different link loads ρ.

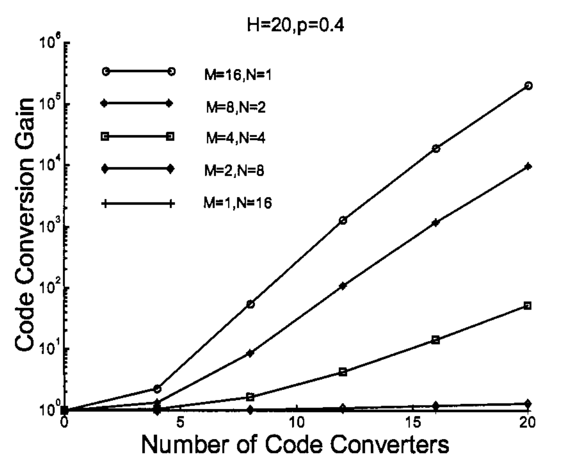

Fig.6 The code conversion gain versus the number of code converters along at link load of 0.4 with different value of M and N.

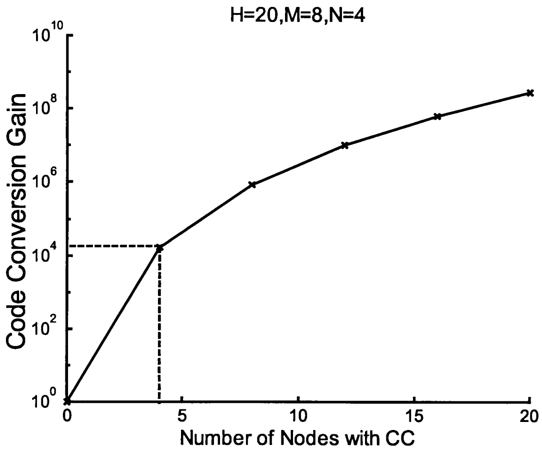

Fig.7 The code conversion gain at ρ =0.4 when code conversion is sparsely added to the path already has WCs.