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NMR: A New Approach for Optimal Design of Strictly Non-Blocking Multistage Interconnection Networks

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Abstract: In this research, a new approach to an optimal design of strictly Non-blocking Multistage Recursive (NMR) interconnection networks and then a CNMR (Clos NMR) is introduced. In designing strictly non-blocking multistage interconnection networks the three factors: number of switching elements or crosspoints (C_N), maximum number of crosspoints or switching elements on signal transfer path (P_N) and maximum number of connection may tolerance while passing from input to output (S_N), play a significant and important role as far as hardware cost, fault tolerance, scalability and routing complexity. These factors are computed and displayed through applying mathematical formula and equations of multistage interconnection networks crossbar, benes, clos, NMR and CNMR. These factors are indicated to be more optimal values in proposed of NMR and CNMR than other multistage interconnection networks with the values being O ($N\sqrt{N}$), O ($\log_2\sqrt{N}$) and a constant value respectively. Therefore, as a result of decreasing the complexity of internal connections and the number of crosspoints or switching elements which are needed in signal transfer path, this network can be used in the multistage interconnection network switches of circuit switching and packet switching with the various sizes.

Key words: Crosspoints, strictly non-blocking multistage interconnection network, clos, crossbar, benes

INTRODUCTION

Optimizing the strictly non-blocking multistage interconnection networks has served as one of the extensive research areas after the introduction and publication paper of clos (Hwang *et al*., 2003; Clos, 1953). These networks have been selected because of their economical, regularity, cost effectiveness and technicality characteristics (Liotopoulos and Logothetis, 2000), as well as, modularity, scalability, measurability, fault tolerant, high efficiency, having multi-passage tracking and routing (Liotopoulos, 2001). In Vaez and Lea (2000), a multistage Banyan architecture was proposed that has much maximum number of crosspoints on signal transfer path and number of crosspoints. Tree-Hypercube (Almobaideen *et al*., 2007) and Mesh-Hypercube (Al-Mahadeen and Omari, 2004), are two types of this networks used extensively in telephone switching and optical fiber networks. They are also used for data communication between memory components with the least propagation delay in parallel processing systems and multiprocessors (Ngo, 2003).

A multistage interconnection network can appear in various forms such as a strictly non-blocking, wide-sense non-blocking, rearrangeable non-blocking and blocking network (Hwang and Liaw, 2000). If a pair of inputs and outputs can always be connected without any considerations, the network is called strictly non-blocking. If a routing mechanism and modification is required to connect each pair of input and output, the network is called wide-sense non-blocking. A rearrangeable non-blocking network refers to the one in which to connect each input and output pair, a modification in the arrangement and rerouting of other input and output pairs must be applied. If a pair of inputs and outputs cannot be connected under any conditions, the network is called a blocking network (Yang and Wang, 2005). The dominating conditions in different types of interconnection networks are discussed in form of theories in (Chang *et al*., 2004). The complexity criteria of multistage interconnection networks (Coppo *et al*., 1993; Gragopoulos and Pavlidou, 1997) are determined and evaluated according to three factors of C_N, P_N and S_N.

Definition 1: C_N refers to the number of crosspoints or Switching Elements (SE_s) in multistage interconnection networks which is equal to the hardware cost of network.

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Definition 2: P_N refers the maximum number of crosspoints or SE_s on signal transfer path multistage interconnection networks which indicate the delay propagation in multistage interconnection networks.

Definition 3: S_N is the maximum number of connections that may tolerance while passing from input to output multistage interconnection networks.

The C_N, P_N and S_N are equal in Crossbar and Benes networks and are computed according to $O(N^2)$, $O(N)$ and $O(N)$, respectively (Salehnamadi and Fesharaki, 2002). These factors in clos network are calculated and set as $O(N\sqrt{N})$, $O(\sqrt{N})$ and $O(\sqrt{N})$, respectively. However, it will be shown that these factors enjoy an optimal conditions in NMR and eventually, in CNMR are equal to $O(N\sqrt{N})$ and $O(\log_2\sqrt{N})$ and a constant value, respectively. The rest of the study is organized as follows:

First, the abovementioned factors are studied and computed in crossbar, benes and clos multistage interconnection networks. Afterwards, the design of proposed NMR and CNMR interconnection networks is discussed and the mentioned factors are analyzed. Then the evaluation and comparison of the results are described. Finally, the findings are discussed.

CROSSBAR, BENES AND CLOS MULTISTAGE INTERCONNECTION NETWORKS

Here, the three factors C_N, P_N and S_N are studied and computed in crossbar, benes and clos multistage interconnection networks.

Crossbar non-blocking multistage interconnection network: Crossbar strictly non-blocking multistage interconnection network with N number of input and M number of output is shown in Fig. 1.

Considering M = N, the three factors of C_N, P_N and S_N are computed as follows:

$C_N = N*N = N^2$
$P_N = N+N-1 = 2N-1$
$S_N = Min(N, N)-1 = N-1$

Benes non-blocking multistage interconnection network: Figure 2 shows a Benes non-blocking multistage interconnection network with N number of input and M number of output. This network is called Benes N.

The three factors of C_N, P_N and S_N are computed as follows:

$C_N = N/2*2*2+2*N/2*N/2+N/2*2*2 = N^2/2+4N$
$P_N = (2+2-1)+(N/2+N/2-1)+(2+2-1) = N+5$
$S_N = Min(2.2)-1+Min(N/2,N/2)-1+Min(2.2)-1 = N/2+1$

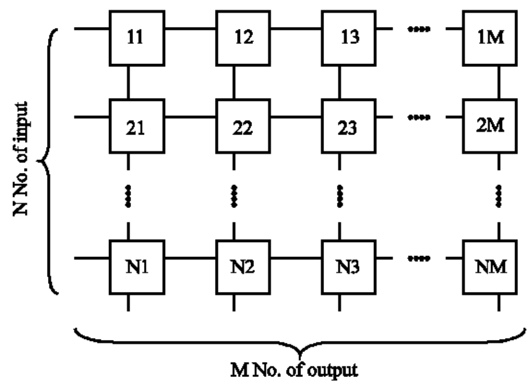

Fig. 1: Structure of a crossbar network with N input and M output

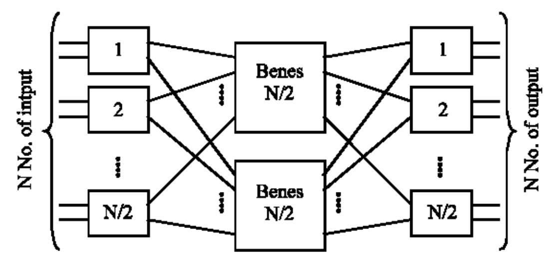

Fig. 2: Structure of a Benes non-blocking multistage interconnection network with N input and output

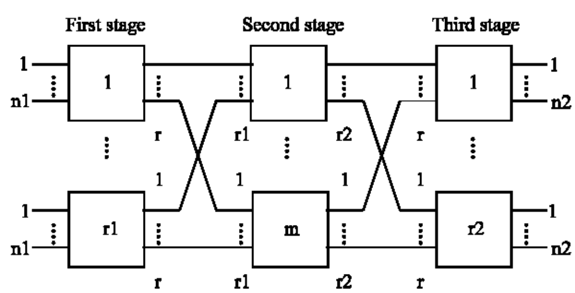

Fig. 3: Structure of a Clos three-stage interconnection network C (n_1, r_1, m, r_2, n_2)

Clos non-blocking three-stage interconnection network: This type of network is shown in Fig. 3 as C (n_1, r_1, m, r_2, n_2).

This network consists of N number of input and M number of output while it has r1 number of n_1*m switches in the first stage, m number of r_1*r_2 switches in the middle stage and r2 number of m*n_2 switches in the third stage. If N equals M, then $n_1 = n_2$ and $r_1 = r_2$. Therefore, we will have in the first stage r number of m*n switches, in the middle stage m number of r*r switches and in the third stage r number of m*n switches. In the optimal case, $N = n^2$, n = r and m = 2n-1 will assure the strictly non-blocking character of the network (Holmberg, 2008). Therefore, the three factors of C_N, P_N and S_N are computed in this type of network as follows:

$$C_N = r*C_{n*m} + m*C_{r*r} + r*C_{m*n} = r*n*m + m*r*r + r*m*n = r*m*(2n+r)$$

$$C_N = n*(2n-1)*(2n+n) = 3n^2*(2n-1) = 3N*(2\sqrt{N}-1)$$

$$P_N = P_{n*m} + P_{r*r} + P_{m*n} = (n+m-1)+(r+r-1)+(m+n-1) = 2n+2r+2m-3$$

$$P_N = 4n+2(2n-1)-3 = 8n-5 = 8\sqrt{N}-5$$

$$S_N = S_{n*m} + S_{r*r} + S_{m*n} = Min(n,m)-1+Min(r,r)-1+Min(m,n)-1 = n-1+r-1+n-1$$

$$S_N = 3n-3 = 3(\sqrt{N}-1)$$

NMR_{N*M} NON-BLOCKING MULTISTAGE RECURSIVE INTERCONNECTION NETWORK

Having a recursive structure and breaking down a problem into a group of smaller problems are of great importance in extensive and complex network designs. Therefore, a strictly non-blocking multistage interconnection network N*M can be designed in a recursive way through strictly non-blocking multistage interconnection networks of N*M/2 or N/2*M or N/2*M/2 and by using 1*2 and 2*1 switches. This strictly non-blocking multistage recursive interconnection network N*M is named as NMR_{N*M}. In special cases, if the number of inputs equals the number of output (N = M), the network is called a non-blocking multistage recursive interconnection network of N or a NMR_N. To prove that the interconnection multistage network is strictly non-blocking, the following theorems are discussed.

Theorem 1: A strictly non-blocking multistage interconnection network N*M can be constructed by shuffling and exchanging the inputs of two strictly non-blocking multistage interconnection network N*M/2 with the outputs of N number of 1*2 switches (Fig. 4).

Proof: Let's assume that $I_{(N)} = \{1, 2,..., N\}$ and $O_{(M)} = \{1, 2,..., M\}$ are, respectively, the inputs and outputs set of a strictly non-blocking multistage interconnection network N*M. Also, let's assume that $I_{1(N)} = I_{2(N)} = \{1,2,...,N\}$, $O_{1(M/2)} = \{1, 2,..., M/2\}$ and $O_{2(M/2)} = \{M/2+1, M/2+2,..., M\}$ are, respectively, the inputs and outputs set of two strictly non-blocking multistage interconnection networks of N*M/2. As the outputs of N number of 1*2 switches connect to the inputs of two strictly non-blocking multistage interconnection networks N*M/2 according to a shuffle-exchange pattern, each input $i \in I_{(N)}$ can connect through one of the N switch 1*2 to one of sets $I_{1(N)}$ or $I_{2(N)}$ and through one of the two

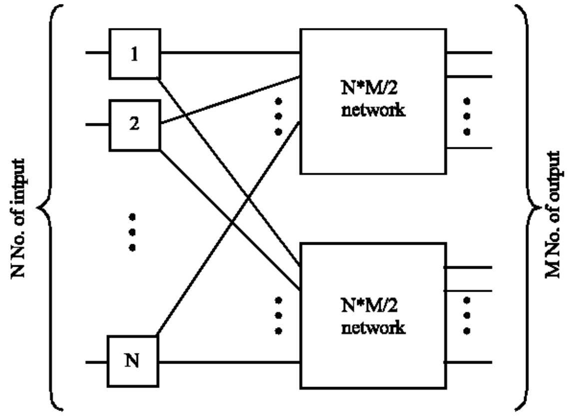

Fig. 4: Strictly non-blocking multistage recursive interconnection network N*M constructed from 1*2 switches and N*M/2 networks

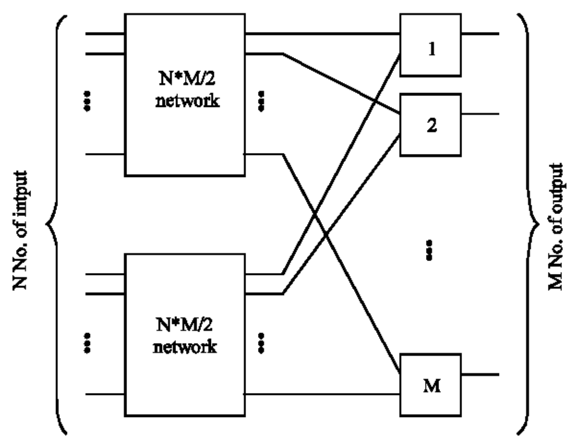

Fig. 5: Strictly non-blocking multistage recursive interconnection network N*M constructed from N/2*M networks and 2*1 switches

strictly non-blocking multistage interconnection networks N*M/2 to any output $j \in O_{(M)}$ non-blocking in any given time. As a result, any $i \in I_{(N)}$ input can connect to each $j \in O_{(M)}$ output without any blocking.

Theorem 2: A strictly non-blocking multistage interconnection network N*M can be constructed by shuffling and exchanging the outputs of two strictly non-blocking multistage interconnection network N/2*M with the inputs of M number of 2*1 switches (Fig. 5).

Proof: Let's assume that $I_{(N)} = \{1, 2,..., N\}$ and $O_{(M)} = \{1, 2,...,M\}$ are, respectively, the inputs and outputs set of a strictly non-blocking multistage interconnection network N*M. Also, let's assume that $I_{1(N/2)} = \{1,2,...,N/2\}$, $I_{2(N/2)} = \{N/2+1, N/2+2,..., N\}$ and $O_{1(M)} = O_{2(M)} = \{1, 2,...,M\}$

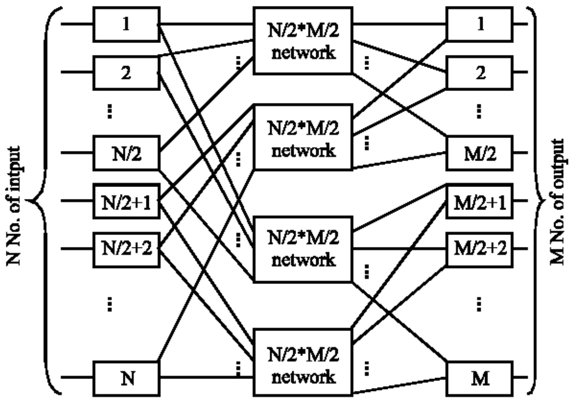

Fig. 6: Strictly non-blocking multistage recursive interconnection network N*M constructed from 1*2 switches, N/2*M/2 networks and 2*1 switches

are, respectively, the inputs and outputs set of two strictly non-blocking multistage interconnection networks of N/2*M. Each input $i \in I_{(N)}$ can connect through one of the strictly non-blocking multistage interconnection networks N/2*M to one of the two $O_{1(M)}$ or $O_{2(M)}$ in any given time. On the other hand, as the outputs of the two strictly non-blocking multistage interconnection networks N/2*M are connected to M inputs switches 2*1 in a shuffle-exchange pattern, any element of $O_{1(M)}$ or $O_{2(M)}$ can connect to any output $j \in O_{(M)}$ through a 2*1 switch without any blocking. Therefore, any $i \in I_{(N)}$ input can connect to any $j \in O_{(M)}$ output with no blocking.

Theorem 3: A strictly non-blocking multistage interconnection network N*M can be constructed by shuffling and exchanging the inputs of four strictly non-blocking multistage interconnection network N/2*M/2 with the outputs of N number of 1*2 switches and its outputs with M switches 2*1 (Fig. 6).

Proof: Considering Theorem 3, in a number of stages and in a recursive mode this network can be converted into a strictly non-blocking multistage recursive interconnection network k*p and simple switches 1*2 and 2*1, assuming that the values of N/k and M/p are exponents of number two. In other words, the network NMR_{N*M} is converted into a number of switching elements 1*2 and 2*1 and number of k*p networks after some stages.

Definition 4: An NMR_{N*M} network, which is converted to a strictly non-blocking multistage recursive interconnection network k*p and simple switching elements 1*2 and 2*1 after multiple of stages is called $NMR_{N*M(k*p)}$.

Here, the three criteria C_N, P_N and S_N in $NMR_{N*M(k*p)}$ networks are studied and calculated, using the following theorems.

These factors (C_N, P_N and S_N) are assumed as C_{k*p}, P_{k*p} and S_{k*p} in strictly non-blocking multistage interconnection network of k*p.

Theorem 4: In NMR_{k*M} strictly non-blocking multistage recursive interconnection network the value of C_{k*M} is equal to:

$$C_{k*M} = k*(M/p-1)+(M/p)*C_{k*p}$$

Proof: According to Theorem 1, this network is constructed by shuffling and exchanging the inputs of two strictly non-blocking multistage interconnection network k*M/2 with the k outputs of 1*2 switches. Therefore, C_{k*M} is equal.

$$C_{k*M} = k+2C_{k*M/2} = k+2(k+2C_{k*M/4}) = k+2k+4C_{k*M/4}$$
$$C_{k*M} = k+2k+4(k+2C_{k*M/8}) = k+2k+4k+8C_{k*M/8}$$
$$C_{k*M} = k+2k+4k+\ldots+(2^{i-1})*k+(2^i)*C_{k*p} = k*(2^i-1)+(2^i)*C_{k*p}$$

Assuming that $M/p = 2^i$ or $p = M/2^i$:

$$C_{k*M} = k*(M/p-1)+(M/p)*C_{k*p}$$

Theorem 5: In NMR_{N*p} strictly non-blocking multistage recursive interconnection network the value of C_{N*p} is equal to:

$$C_{N*p} = p*(N/k-1)+(N/k)*C_{K*p}$$

Proof: According to Theorem 2, this network is constructed by shuffling and exchanging the outputs of two strictly non-blocking multistage interconnection network N/2*p with the p inputs of 2*1 switches. Therefore, C_{N*p} is equal.

$$C_{N*p} = p+2C_{N/2*p} = p+2(p+2C_{N/4*p}) = p+2p+4C_{N/4*p}$$

Assuming that $N/k = 2^j$ or $k = N/2^j$:

$$C_{N*p} = p*(N/k-1)+(N/k)*C_{k*p}$$

Theorem 6: In NMR_{N*M} strictly non-blocking multistage recursive interconnection network which is constructed by k*p strictly non-blocking multistage interconnection network and 1*2 and 2*1 simple switching elements, the value of $C_{N*M(k*p)}$ is equal to:

$$C_{N*M(k*p)} = (C_{k*p}+k+p)*(N*M)/(k*p)-(N+M)$$

Proof: According to Theorem 4 and Theorem 5:

$C_{N*M(k*p)} = N*(M/p-1)+(M/p)*C_{N*p}$
$C_{N*M(k*p)} = N*M/p-N+(M/p)*(P*(N/k-1)+(N/k)*C_{k*p})$
$C_{N*M(k*p)} = N*M/p-N+N*M/k-M+(N*M/k*p)*C_{k*p}$
$C_{N*M(k*p)} = (C_{k*p}+k+p)*(N*M)/(k*p)-(N+M)$

If in a strictly non-blocking multistage recursive interconnection network the number of inputs equals the number of outputs, N= M, called $NMR_{N(k*p)}$, then:

$$C_{N(k*p)} = (C_{k*p}+k+p)*(N^2/(k*p))-2N$$

And also if in an NMR_N network, strictly non-blocking multistage interconnection networks with the equal number of inputs and outputs are used (k = p), then:

$$C_{N(k)} = (C_k+2k)*(N^2/k^2)-2N$$

Theorem 7: In the network discussed in Theorem 6, the value of $P_{N*M(k*p)}$ is equal to:

$$P_{N*M(k*p)} = P_{k*p}+\log_2((N*M)/(k*p))$$

Proof: It is proved in a similar way. However, in a specific condition if N = M, then:

$$P_{N(k*p)} = P_{k*p}+\log_2(N^2/(k*p))$$

And if k = p, then:

$$P_{N(k)} = P_k+2\log_2(N/k)$$

Theorem 8: In the network discussed in Theorem 6, the value of $S_{N*M(k*p)}$ is equal to:

$$S_{N*M(k*p)} = S_{k*p}$$

Proof: To determine the factor $S_{N*M(k*p)}$ in NMR_{N*M} network, it should be noted that switches 1*2 and 2*1 have no effect on $S_{N*M(k*p)}$, since Min (2, 1)-1 = Min (1, 2)-1 = 0 and therefore, $S_{N*M(k*p)}$ is dependent only on the value of this parameter in k*p strictly non-blocking multistage interconnection network, then:

$$S_{N*M(k*p)} = S_{k*p}.$$

$CNMR_{N*M}$ STRICTLY NON-BLOCKING MULTISTAGE RECURSIVE INTERCONNECTION NETWORK

Since in clos three-stage interconnection network C_N has an optimal value and $NMR_{N(k)}$ network optimizes the values of P_N and S_N, we can use an NMR $_{N(k)}$network in designing a clos strictly non-blocking three-stage interconnection network. This type of network is called Clos strictly Non-blocking Multistage Recursive interconnection network or $CNMR_{N(k)}$, which is shown in Fig. 7.

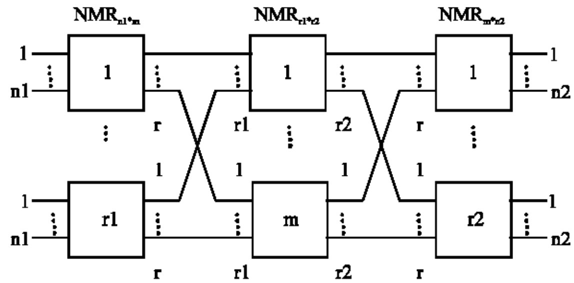

Fig. 7: Clos strictly Non-blocking Multistage Recursive interconnection network in $CNMR_{N*M}$

Considering the following lemmas, we analyze and compute the three factor C_N, P_N and S_N in $CNMR_{N(k)}$ network.

Lemma 1: In $CNMR_{N(k)}$ network, the value of C_N is equal to:

$$C_N = [6(C_k+2k)/k^2]*N\sqrt{N}-10N$$

Proof: In order to calculate the value of C_N in $CNMR_{N(k)}$ network, first it must be calculated in Clos strictly non-blocking three-stage interconnection network. It will be as follows:

$$C_N = r*C_{n*m}+m*C_{r*r}+r*C_{m*n} = 2r*C_{n*m}+m*C_{r*r}$$

In an optimum case of Clos strictly non-blocking three-stage interconnection network, r = n = $\sqrt{N}$ and m $\geq$ 2n-1. Furthermore, as the number of inputs and outputs in any $NMR_{N(k)}$ network must be an exponentiation of two, then m = 2n.

As a result, in a Clos strictly non-blocking three-stage interconnection network we will have:

$$C_N = 2n*C_{n*2n}+2n*C_{n*n}=2n*(C_{n*2n}+C_{n*n})$$

On the other hand, in $CNMR_{N(k)}$ network, an $NMR_{N*M(k)}$ network is used to calculate the values of C_{n*2n} and C_{n*n}. According to Theorem 6:

$C_{n*n(k)} = C_{n(k)} = (C_k+2k)*(n^2/k^2)-2n$
$C_{n*2n(k)} = (C_k+2k)*(2n^2/k^2)-3n$

According to the above equation:

$C_N = 2n*[(C_k+2k)*(2n^2/k^2)-3n+(C_k+2k)*(n^2/k^2)-2n]$
$C_N = [6(C_k+2k)/k^2]*n^3-10n^2$

And considering $n = \sqrt{N}$, then:

$C_N = [6(C_k+2k)/k^2]*N\sqrt{N}-10N$

Lemma 2: Value of P_N in $CNMR_{N(k)}$ network equals to:

$P_N = 6\log_2\sqrt{N}-6\log_2 k+3P_k+2$

Proof: As in Lemma 1, in Clos strictly non-blocking three-stage interconnection network factor P_N is as following:

$P_N = P_{n*m}+P_{r*r}+P_{m*n} = P_{n*2n}+P_{n*n}+P_{2n*n}$

On the other hand, based on Theorem 7, in an $NMR_{N*M(k)}$ network the value of $P_{N*M(k)}$ equals:

$P_{N*M(k)} = P_k+\log_2(N*M/k^2)$
$P_{2n*n(k)} = P_{n*2n(k)} = P_k+\log_2(2n^2/k^2) = P_k+\log_2 2+\log_2(n^2/k^2) = 2\log_2(n/k)+P_k+1$
$P_{n*n(k)} = P_k+\log_2(n^2/k^2) = 2\log_2(n/k)+P_k$

According to the above equations, the value of P_N in $CNMR_{N(k)}$ network equals:

$P_N = 2\log_2(n/k)+P_k+1+2\log_2(n/k)+P_k+2\log_2(n/k)+P_k+1 = 6\log_2 n-6\log_2 k+3P_k+2$

Considering $n = \sqrt{N}$, then:
$P_N = 6\log_2\sqrt{N}-6\log_2 k+3P_k+2$

Lemma 3: In $CNMR_{N(k)}$ network, the value of S_N equals:
$S_N = 3S_k$

Proof: As in Lemma 1 and Lemma 2, in order to calculate the value of factor S_N in $CNMR_{N(k)}$ networks, first the value of this factor must be calculated in Clos strictly non-blocking three-stage interconnection network as follows:

$S_N = S_{n*m}+S_{r*r}+S_{m*n} = S_{n*2n}+S_{n*n}+S_{2n*n}$

On the other hand, according to Theorem 8, in $NMR_{N*M(k)}$ network, the value of $S_{N*M(k)}$ equals S_k. Therefore the value of factor S_N in $CNMR_{N(k)}$ networks, is calculated as follows:

$S_N = S_k+S_k+S_k = 3S_k$.

DISCUSSION AND PERFORMANCE EVALUATION

Here, the proposed NMR and CNMR networks are compared with Crossbar, Benes and Clos multistage interconnection networks based on the three factors of C_N, P_N and S_N.

Comparing the criterion of C_N: According to the computed equations, Fig. 8 shows the number of crosspoints or switching elements (C_N) in different networks.

In other words, according to the different values of N and k, the obtained results can be shown in Fig. 8.

As it can be shown in Fig. 8, the C_N in the $CNMR_{N(8)}$ network enjoys a more optimal value compared to the other types of networks.

Comparing the criterion of P_N: According to the computed equations, Fig. 9 shows the maximum number of crosspoints or switching elements existing in the transferring path (P_N) in different types of networks.

According to the different values of N and k, the obtained results can be shown in Fig. 9.

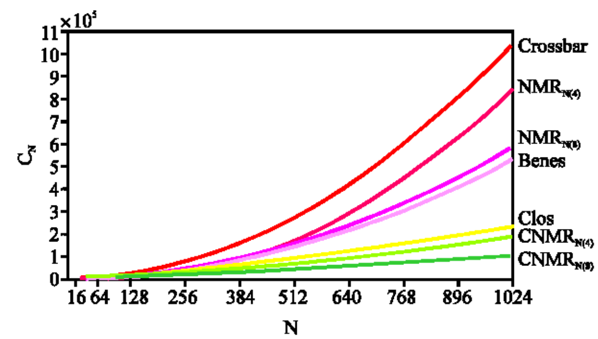

Fig. 8: Comparative graph between C_N in NMR, CNMR, crossbar, benes and clos networks

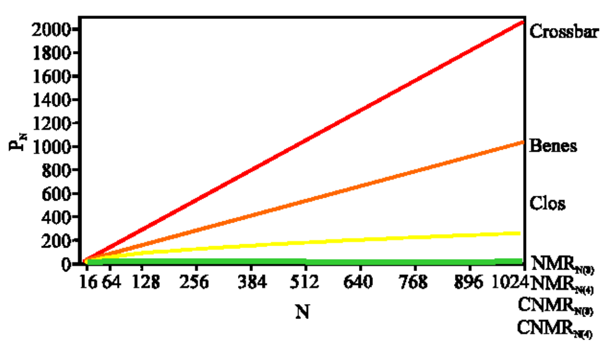

Fig. 9: Comparative graph between P_N in NMR, CNMR, crossbar, benes and clos networks

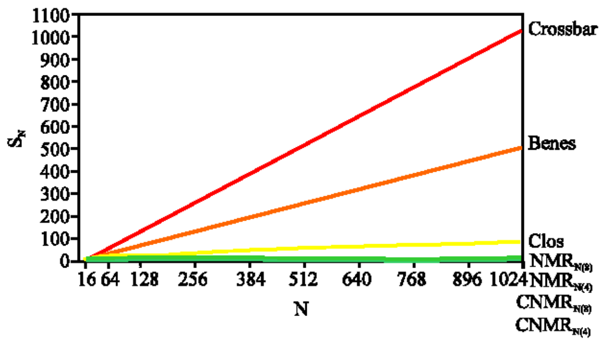

Fig. 10: Comparative graph between S_N in NMR, CNMR, Crossbar, Benes and Clos networks

As Fig. 9 shows, the P_N in the NMR $_{N(4)}$ NMR $_{N(8)}$ $CNMR_{N(4)}$ and $CNMR_{N(8)}$ network enjoys a more optimal value compared to the other types of networks.

Comparing the criterion of S_N: According to the computed equations, Fig. 10 shows the maximum number of connections passing from input to output (S_N) in different types of networks.

According to the different values of N and k, Fig. 10 is shown.

As Fig. 10 shows, the S_N in the $NMR_{N(4)}$, $NMR_{N(8)}$, $CNMR_{N(4)}$ and $CNMR_{N(8)}$ network enjoys a more optimal value compared to the other types of networks.

CONCLUSION

Three criteria of C_N, P_N and S_N play a important role in the design of interconnection networks. The optimal multistage interconnection networks is a network with the and least value of C_N, P_N and S_N, which is distributed with the minimum overhead and simpler routing algorithm. The obtained results indicate that Crossbar and Benes networks, though being non-blocking and simple in routing mechanism, have higher factors of C_N, P_N and S_N, hence higher cost. A Clos network, on the other hand, has fewer number of C_N, but the S_N and P_N factors are more costly. While in the proposed networks NMR and finally CNMR, the three factors of C_N, P_N and S_N have optimal values of O ($N\sqrt{N}$), O($\log_2\sqrt{N}$) and a constant value, respectively. As results, this networks can be used and applied extensively in parallel processing systems and high speed telecommunication networks.

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