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Role of MUX and DEMUX in Enhancing the Reliability of MIN

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Abstract- **Multistage Interconnection Networks (MIN) play vital role in routing of large data for highly efficient parallel processors and hence their designing is an important factor which decides the performance of these systems. So MIN are required to be highly reliable and fault tolerant. To increase the fault tolerance of MIN beyond its fixed limit extra hardware in form of extra stage has been added in past. But with the increased number of paths between each source-destination (S-D) node pair, it does not provide disjoint paths while adding extra hardware complexity and cost to the network. Hence reliability does not improve as expected. Recently a new method has been proposed in literature to increase reliability of networks by making use of MUX and DEMUX at input and output terminals respectively and acclaimed highest reliability. In this paper the method of using MUX and DEMUX has been used for all other counterparts of one of the regular MIN that is Shuffle Exchange Network (SEN). Reliability and cost of all SEN MIN have been analyzed for different sizes of MUX and DEMUX. A new parameter i.e. Reliability Cost Ratio has also been introduced in this paper. According to the results achieved it has been stated that with the increased size of MUX and DEMUX number of path and reliability of SEN MIN has increased but cost has also been increased due to which reliability Cost Ratio decreases. A thorough analysis shows that SEN- MIN network with highest reliability Cost Ratio can be used as most reliable and cost effective networks for up to 4×1 and 1×4 size of MUX and DEMUX at input and output respectively with maximum number of disjoint paths having minimum path length.**

Keywords—Multistage Interconnection Network (MIN), Shuffle Exchange Network (SEN), Reliability, Cost, Reliability Cost Ratio (RCR), Multiplexer (MUX), Demultiplexer (DEMUX).

I. INTRODUCTION

In parallel processing system a communication system is required to connect different processors to their memory module and peripheral devices. MIN are used as communication system for these supercomputers due to their self routing based asynchronous data transfer mode (ATM) technology [1-20]. MIN provide a cost effective and compromised communication (between expensive, highly efficient fully crossbar Network and cost effective low performance shared bus network) between processes and memory module [1-7]. So designing of MIN is most challenging task as the performance of parallel processing systems totally depends on the performance of these MIN [5-8].

N×N MIN topology consists of N number of inputs and outputs with $\log_2 N$ switching stages consisting of a×a Switching Element (SE) and 'N/a' number of switches per stage [7-13]. MIN can be categorized into two categories (i) Regular MIN and (ii) Irregular MIN [5-7]. Regular topology of MIN consists of equal number of switching element per stage where as irregular MIN topology consists of an unequal number of SE per stage. Regular MIN is simple in construction with less hardware complexity and an equal path length for each source destination (S-D) node pair as compared to irregular topology [4-6]. N×N SEN is a regular MIN with 2×2 fully crossbar SE. SEN MIN has been used and analyzed by many researchers in past due to its simple design topology and minimum path delay for transmission [7-15]. SEN is a unique path MIN i.e. there is only one path between each S-D node pair so it provides no fault tolerance and possess low reliability in its basic topology. Fault tolerance of a system can be defined as the ability to perform in desirable limit even in presence of faults [11-15, 19-20] where as reliability of network may be defined as desirable performance of networks with any normal or critical situation [8]. The main issue in SEN MIN is to make this network reliable and fault tolerant. The common method to resolve this issue is to increase number of paths between each S-D node pair of a network called redundancy to bear faults and perform reliably [7-10]. General approach to this problem is to increase the number of stages in the networks [7-9, 15]. This method of increasing redundancy have been used in past by many researchers [7-15]. The popularity of this method is because of its low cost and less added complexity to the network. The relationship between increased number of paths per increased number of stages is given by the equation [7, 9] as follows:

Number of path between each S-D node pair = 2^k,

Where k: number of stages increased

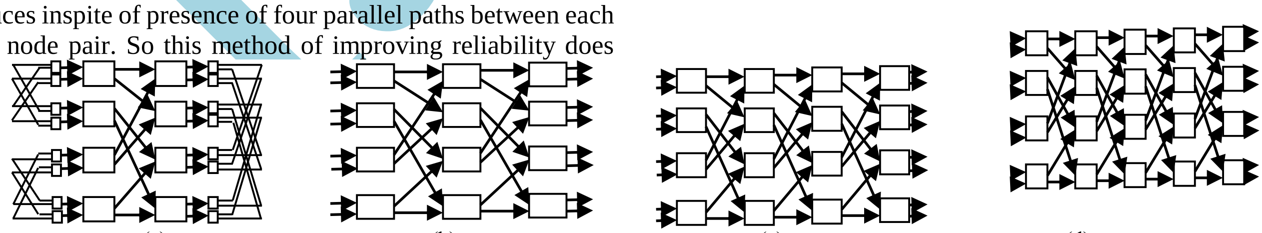
According to the equation given above, number of paths increases with the increased number of stages due to which fault tolerance capability of a network increases and automatically reliability also increases. But it has been found in literature [9] that reliability decreases (or increases to the very small extent) with more number of increased stages. So adding number of stages does not provide an optimum solution to the problem. Another method of increasing reliability and fault tolerance, which has been introduced in literature is by making use of MUX and DEMUX at input and output stages respectively [15-17]. It not only increases the fault tolerance of network but it also provides totally disjoint paths, which increases the reliability to a much higher extent even with the reduced number of stages. Recently SEN- with one minus stage has been introduced, which provides two totally disjoint paths with very bigh reliability then its counterparts. It has been acclaimed [15, 17] that SEN- is atleast one fault tolerant network at each stage including input as well as output stages. In super computer systems where thousands of processors have to be connected in parallel, multiple congestions due to large data traffic can arise at one time and hence more than two paths may fail instantly due to which the network may fail. Hence more than two paths are required for communicating large data in parallel processing systems [9-18]. With this motivation this research has been pursued so as to provide an optimum solution for large data traffics and achieve high reliability with minimum cost and hardware complexity. In this paper different sizes of MUX and DEMUX (up to the size of 8×1/1×8 MUX/DEMUX) have been used at input and output stages and their effect have been analyzed for all SEN MIN. It has been realized that by making use of higher size of MUX and DEMUX reliability improves, but it also increases the cost and complexity of the network. For analysis SEN-, SEN, SEN+ (with one extra stage) and SEN++ (with two extra stages) MIN have been considered. A comparative statement has been generated about up to which size, MUX and DEMUX can be used to increase reliability with lowest added cost and complexity to the network. A new parameter has been introduced in this paper to fix limit between reliability improvement and cost enhancement. The parameter is Reliability Cost Ratio (CRC) which is defined as reliability achieved per unit cost for a given network. This parameter will impose limit on the size of MUX and DEMUX which can be used to increase the reliability with minimum cost overhead.

Rest of the paper is organized in the following structure: Section 2 discusses the backgrounds of SEN MIN. Section 3 discusses the new proposed topologies. Section 4 gives the reliability and cost evaluation of the proposed networks followed by the conclusions drawn and future scope in section 5.

II. BACKGROUNDS

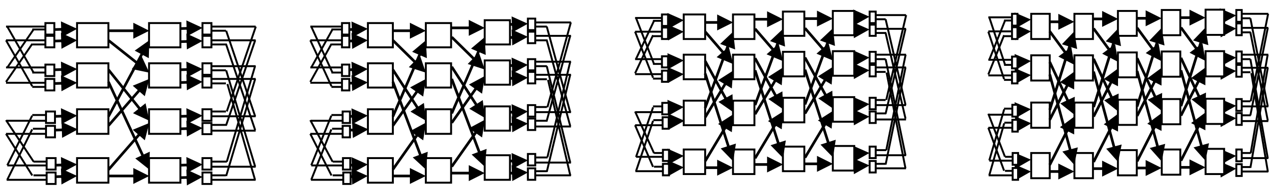
SEN MIN is a unique path MIN with $\log_2 N$ number of stages. To create redundancy in SEN MIN, researchers have increased its number of stages. According to previous research it has been concluded that reliability of SEN MIN increases with the addition of one extra stage (SEN+) [7-18]. This extra stage has added two parallel paths between each S-D node pair which increases the fault tolerance of the network. But if two extra stages are added to SEN network then the reliability reduces inspite of presence of four parallel paths between each S-D node pair. So this method of improving reliability does not provide optimum result. In ref. [15, 17] 1×2/2×1 MUX/DEMUX have been used to increase reliability of network and concluded that this method effectively increases the reliability of the network and provide disjoint path between each S-D node pair. In this paper the method used in ref. [15-17] of improving reliability has been explored by making use of higher size of MUX and DEMUX to improve reliability. In ref [15, 17] use of MUX/DEMUX was limited to SEN-network only but in this paper MUX and DEMUX have been used for other SEN MIN such as SEN, SEN+, SEN+2 and reliability analysis for these network have been done. In this paper it has been shown that with the use of higher size of MUX and DEMUX reliability increases for all SEN MIN. This is due to the increase in number of disjoint paths in these networks. But cost of all these networks also increases abruptly which is undesirable. So a compromise has to be made between reliability improvement and cost enhancement of MIN. Hence a new parameter named as Reliability Cost Ratio (RCR) has been introduced here which gives the reliability improvement of the network by each added disjoint paths per unit cost. According to this parameter a limit can be put on the size of MUX and DEMUX which can be used in the network to increase its reliability. It has been shown that SEN- with 4×1/1×4 MUX/DEMUX has optimum RCR with four disjoint paths for each S-D node pair. So this network can be used as MIN with minimum number of stages, affordable cost, less hardware complexity and very high reliability. The results are shown in the proceeding section. The main contributions of this paper are summarized as:

1. Different architectures of all available SEN MIN with different size of MUX and DEMUX have been proposed.
2. The complicated structures of these MIN are reduced in simple series parallel reliability block diagram (RBD) so as to analyze their reliability with transparency.
3. Terminal reliability has been analyzed for each network by considering different values of switching element reliability (R_{SE}) ranging from 0.9 to 0.99.
4. A new parameter named as Reliability Cost Ratio has been proposed to associate reliability with respect to cost.
5. Methodology used here to increase reliability is simple and can be extended to any other Complex network topology.



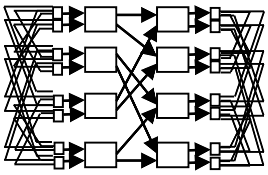
(a) (b) (c) (d)

Fig. 1: Topologies of a) SEN- MIN, b) SEN MIN, c) SEN+ MIN and d) SEN+2



(a) (b) (c) (d)

Fig. 2: Proposed Topologies of all SEN with 2×1/1×2 MUX/DEMUX a)SEN-, b)SEN, c)SEN+ and d) SEN+2



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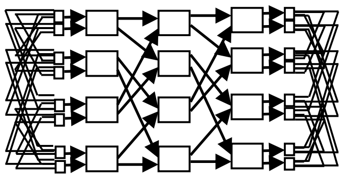

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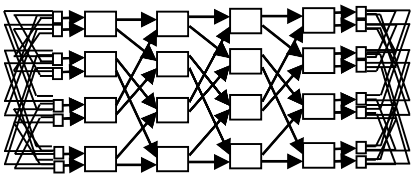

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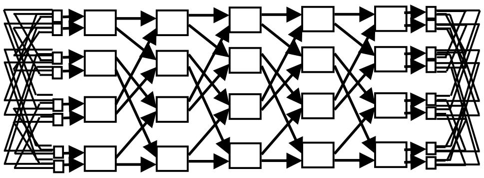
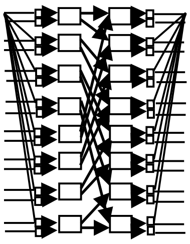


(d)

Fig. 3: Proposed Topologies of all SEN with 4×1/1×4 MUX/DEMUX a)SEN-, b)SEN, c)SEN+ and d) SEN+2



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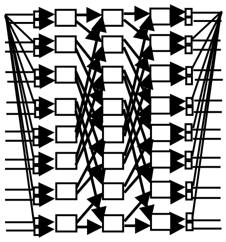

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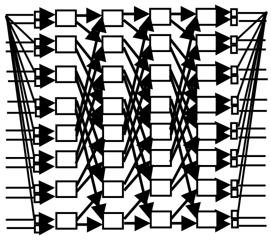

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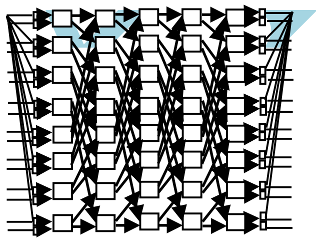
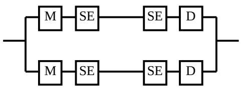


(d)

Fig. 4: Proposed Topologies of all SEN with 8×1/1×8 MUX/DEMUX a) SEN-, b) SEN, c) SEN+ and d) SEN+2



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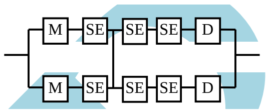

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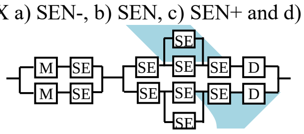

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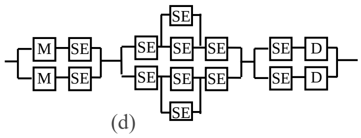
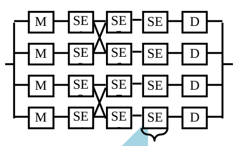


(d)

Fig. 5: Reliability Block Diagram of all SEN with 2×1/1×2 MUX/DEMUX a) SEN-, b) SEN, c) SEN+ and d) SEN+2



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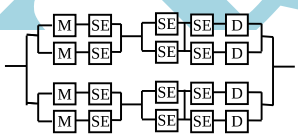

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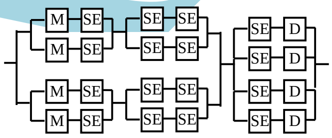

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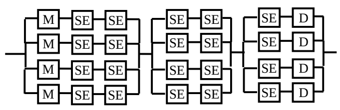
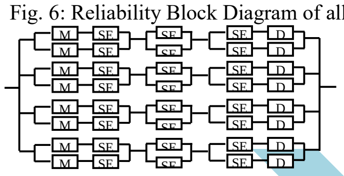


(d)

Fig. 6: Reliability Block Diagram of all SEN with 4×1/1×4 MUX/DEMUX a) SEN-, b) SEN, c) SEN+ and d) SEN+2



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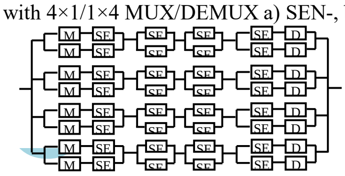

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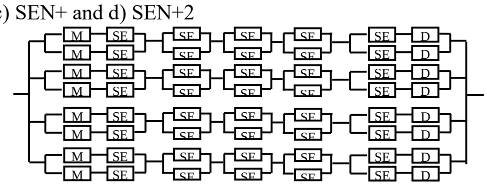

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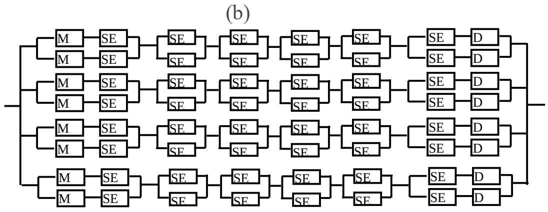


(c)

Fig. 7: Reliability Block Diagram of all SEN with 8×1/1×8 MUX/DEMUX a)SEN-, b)SEN, c)SEN+ and d) SEN+2.

III. Proposed Topology

In this paper all SEN MIN have been analyzed because of their topological equivalent to other class of networks such as binary-n-cube network, generalized cube network, Omega network etc. and hence analysis done for SEN MIN is equally applicable for the above mentioned networks too. As already been discussed N×N SEN MIN is single path MIN with N inputs and outputs connected through $\log_2 N$ number of stages comprising of N/2 SE at each stage. SEN+ is SEN MIN with one additional stage (i.e. $\log_2 N+1$ number of stages) with same topology. It provides two paths for each S-D node pair. SEN+2 comprises of two additional stages (i.e. $\log_2 N+2$ number of stages) with same topology and provides four paths between each S-D node pair. SEN- is SEN MIN with one less stage which uses MUX and DEMUX at input and output stage respectively. It provides two totally disjoint paths for each S-D node pair. Fig. 1 shows the topology of all four above mentioned networks for 8×8 network size. Fig. 2 and 3 show all four network topologies with 2×1/1×2 and 4×1/1×4 size of MUX and DEMUX at input and output stages. For 8×1/1×8 size of MUX/DEMUX all SEN MIN with network size of 16 ×16 has to be considered which is shown in Fig. 4.

IV. Reliability And Cost Analysis

Reliability of a system can be defined as the probability of atleast one fault free path exists between each S-D node pair [7, 9, 11, 15]. It is an important parameter to evaluate the performability of MIN with any network topology. For reliability evaluation of SEN MIN the complicated topologies of their structure have been reduced into simple series parallel RBD as shown in Fig. 5, 6 and 7. Table 1 shows the total number of paths for all four topologies. It has been seen that as the size of MUX and DEMUX increases, the number of paths for each S-D node pair also increases. But reliability is not a function of number of Path availability, so reliability of a network has to be analyzed separately. Using RBD of Fig 5, 6 and 7, terminal reliability equations for all these network have been deduced and shown in Table 2. Reliability of these networks has to be calculated by assuming SE reliability as 'r' where 'r' is a function of time and can be expressed as:

$$r = \int_0^{\infty} e^{-\lambda t}$$

where λ is failure rate = .000001 /sec

The assumptions taken for reliability calculation are as follows:

1. Reliability of 2×1 SE is taken as 'r' (w.r.t. the number of cross-points i.e. 2×2 SE has 4 cross-points 4/4 = 1).
2. Reliability of 1×2/2×1 MUX/DEMUX is taken as 'r1/2'.
3. Similarly for 1×4 and 4×1 MUX/DEMUX is taken as 'r' (for 4 cross-points) and for 1×8/8×1 MUX/DEMUX is taken as 'r2' (for 8 cross-points).

Table 1: Number of Paths for all SEN MIN

Name of N/W	*Number of paths for 2×1/1×2*	*Number of paths for 4×1/1×4*	*Number of paths for 8×1/1×8*
SEN-	*2*	*8*	*32*
SEN	*4*	*16*	*64*
SEN+	*8*	*32*	*128*
SEN+2	*16*	*64*	*256*

Table 2: Reliability equations for all SEN MIN for 2×1/1×2, 4×1/1×4 and 8×1/1×8 size of MUX/DEMUX

S.No.	**Network**	***Size of MUX/DEMUX Used***	**Terminal Reliability Equation**
1	**SEN-**	***2×1/1×2***	$\left[1-\left(1-r^{3}\right)^{2}\right]$
2	**SEN**		$\left[1-\left(1-r^{3/2}\right)^{2}\right]\left[1-\left(1-r^{5/2}\right)^{2}\right]$
3	**SEN+**		$\left[1-\left(1-r^{3/2}\right)^{2}\right]\left[1-\left(1-r^{5/2}(1-(1-r)^{2})\right)^{2}\right]$
4	**SEN+2**		$r^{2}\left[1-(1-r)^{2}\right]\left[1-\left(1-r^{3/2}\right)^{2}\right]^{2}$
1	**SEN-**	***4×1/1×4***	$1-\left\{1-\left[1-\left[1-r^{2}\right]^{2}\right]\left[1-\left[1-r^{2}\right]^{2}\right]\right\}^{2}$
2	**SEN**		$1-\left\{1-\left[1-\left[1-r\right]^{2}\right]\left[1-\left[1-r^{2}\right]^{2}\right]^{2}\right\}^{2}$
3	**SEN+**		$1-\left\{1-\left[1-\left[1-r^{2}\right]^{2}\right]^{2}\right\}^{2}\left\{1-\left(1-r^{2}\right)^{4}\right\}$
4	**SEN+2**		$\left\{1-\left(1-r^{3}\right)^{4}\right\}\left\{1-\left(1-r^{2}\right)^{4}\right\}^{2}$
1	**SEN-**	***8×1/1×8***	$1-\left\{1-\left[1-\left[1-r^{3}\right]^{2}\right]^{2}\left(1-(1-r)^{2}\right)\right\}^{4}$
2	**SEN**		$1-\left\{1-\left[1-\left[1-r^{3}\right]^{2}\right]^{2}\left(1-(1-r)^{2}\right)^{2}\right\}^{4}$
3	**SEN+**		$1-\left\{1-\left[1-\left[1-r^{3}\right]^{2}\right]^{2}\left(1-(1-r)^{2}\right)^{3}\right\}^{4}$
4	**SEN+2**		$1-\left\{1-\left[1-\left[1-r^{3}\right]^{2}\right]^{2}\left(1-(1-r)^{2}\right)^{4}\right\}^{4}$

Table 3: Reliability Value for all SEN MIN for Reliability of SE (R_{SE}) = 0.99 to 0.90

Network Name	Size of MUX/DEMUX	R_{SE}=0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.90
SEN-	2×1/1×2	0.9991	0.9965	0.9924	0.9867	0.9797	0.9713	0.9617	0.9510	0.9393	0.9266
SEN		0.9992	0.9967	0.9926	0.9871	0.9801	0.9718	0.9621	0.9513	0.9392	0.9262
SEN+		0.9992	0.9966	0.9925	0.9868	0.9796	0.9709	0.9608	0.9493	0.9366	0.9226
SEN+2		0.9796	0.9583	0.9363	0.9136	0.8904	0.8666	0.8424	0.8179	0.7931	0.7680
SEN-	4×1/1×4	0.9999999	0.999999	0.99999	0.9998	0.9996	0.999 3	0.9987	0.9978	0.9966	0.9950
SEN		0.999996	0.99999	0.9999	0.9998	0.9995	0.9991	0.9983	0.9972	0.9957	0.9936
SEN+		0.99999	0.99999	0.99999	0.9998	0.9996	0.9993	0.9987	0.9978	0.9966	0.9950
SEN+2		0.99998	0.99997	0.9999	0.9997	0.9994	0.9988	0.9979	0.9965	0.9946	0.9920
SEN-	8×1/1×8	0.99999	0.99999	0.99999	0.99999	0.99998	0.99997	0.99996	0.9999	0.9998	0.9995
SEN		0.99999	0.99999	0.99999	0.99998	0.99997	0.99996	0.9999	0.9999	0.9997	0.9994
SEN+		0.99999	0.99999	0.99999	0.99999	0.99998	0.99997	0.9999	0.9998	0.9996	0.9992
SEN+2		0.99999	0.99999	0.99998	0.99997	0.99996	0.99996	0.9999	0.9998	0.9995	0.9991

Terminal Reliability of all SEN MIN has been calculated according to the equations given in Table 2 with different sizes of MUX/DEMUX and are shown in Table 3. As shown, reliability increases with the increased size of MUX/DEMUX for all SEN MIN, but as the size of MUX/DEMUX increases the cost of network also increases which is undesirable. Fig. 8 (a) and (b) shows the graphical representation of terminal reliability all SEN MIN.

Table 4: Cost functions for all SEN MIN

Name of N/W	*Size of MUX/DEMUX Used*	*Cost Function*
SEN-	*2×1/1×2*	*2N($\log_2 N$+1)*
	4×1/1×4	*2N($\log_2 N$+3)*
	8×1/1×8	*2N($\log_2 N$+7)*
SEN	*2×1/1×2*	*2N($\log_2 N$+2)*
	4×1/1×4	*2N($\log_2 N$+4)*
	8×1/1×8	*2N($\log_2 N$+8)*
SEN+	*2×1/1×2*	*2N($\log_2 N$+3)*
	4×1/1×4	*2N($\log_2 N$+5)*
	8×1/1×8	*2N($\log_2 N$+9)*
SEN+2	*2×1/1×2*	*2N($\log_2 N$+4)*
	4×1/1×4	*2N($\log_2 N$+5)*
	8×1/1×8	*2N($\log_2 N$+10)*

The cost of these networks can be calculated by using a common method i.e. by calculating the switch complexity (the number of gates or cross-point used in a switch). For N×N switch the complexity can be represented by N^2 [9, 11-15, 17]. So for 2×2 SE cost can be calculated as 4. According to this assumption the cost function for all SEN MIN as a function of network size 'N' can be expressed and calculated as shown in Table 4 and 5 respectively. It can be concluded that SEN- MIN has minimum cost as compared to all other MIN with all sizes of MUX/DEMUX. For analyzing the network superiority on the basis of reliability, cost and number of disjoint paths availability a new parameter RCR has been introduced can be expressed as:

RCR = (Reliability × Disjoint paths)/Cost of network

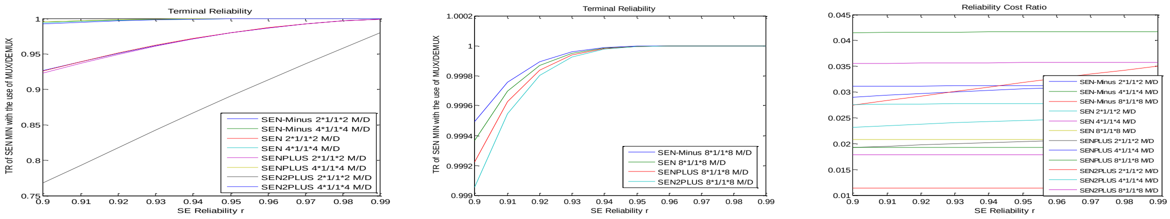
The calculated values of cost and RCR for all SEN MIN for 8×8/16×16 network size is shown in Table 4. It can be concluded form Table 4 that SEN- MIN with 4×1/1×4 MUX/DEMUX has highest RCR as compared to all other networks. It is shown here the SEN- MIN posses best result as a compromise between cost and reliability enhancement with minimum distance between each S-D node pair. Fig 8 (c) shows the graphical representation of RCR for all SEN MIN.

V. Conclusion And Future Scope

MIN are responsible for reliable and efficient communication of big data from processors to their memory modules. SEN MIN are most used and fast improving MIN according to the requirements of parallel computers. So in this paper SEN MIN has been explored and improved by making use of MUX and DEMUX at input and output terminal respectively, to introduce disjoint path in the existing topologies. It has been found that reliability of all SEN MIN have improved with the use of MUX and DEMUX, but there is a huge increase in cost too. From all the calculations done in this paper it has been shown that SEN- MIN with 4×1 and 1×4 MUX and DEMUX has maximum RCR as compared to all other MIN topologies introduced with the high reliability. Although reliability of SEN- MIN with 8×1 and 1×8 MUX and DEMUX has maximum reliability with 0.45% more improvement. Which is commendable as compared to SEN- MIN with 4×1/1×4 MUX/DEMUX, but cost has also been increased by 266%. So with such a small increment in reliability and that hike in cost SEN- MIN with 1×8 and 8×1 MUX and DEMUX may not be affordable. From here it can be concluded that SEN- MIN with 4×1/1×4 MUX/DEMUX can be preferred over all other topologies of SEN MIN with its optimum reliability and cost. For future guidelines same work may be extended to other class of means such as grammar Network and its variants.

Table 5: Calculated cost and Reliability Cost Ratio Values for all SEN MIN

Network Name	Size of MUX/DEMUX	Cost	R_{SE}=0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.90
SEN-	2×1/1×2	64	0.0312	0.0311	0.0310	0.0308	0.0306	0.0304	0.0301	0.0297	0.0294	0.0290
SEN		80	0.0250	0.0249	0.0248	0.0247	0.0245	0.0243	0.0241	0.0238	0.0235	0.0232
SEN+		96	0.0208	0.0208	0.0207	0.0206	0.0204	0.0202	0.0200	0.0198	0.0195	0.0192
SEN+2		112	0.0350	0.0342	0.0334	0.0326	0.0318	0.0310	0.0301	0.0292	0.0283	0.0274
SEN-	4×1/1×4	96	0.0417	0.0417	0.0417	0.0417	0.0417	0.0416	0.0416	0.0416	0.0415	0.0415
SEN		112	0.0357	0.0357	0.0357	0.0357	0.0357	0.0357	0.0357	0.0356	0.0356	0.0355
SEN+		128	0.0312	0.0312	0.0312	0.0312	0.0312	0.0312	0.0312	0.0312	0.0311	0.0311
SEN+2		144	0.0278	0.0278	0.0278	0.0278	0.0278	0.0277	0.0277	0.0277	0.0276	0.0276
SEN-	8×1/1×8	352	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114	0.0114
SEN		384	0.0208	0.0208	0.0208	0.0208	0.0208	0.0208	0.0208	0.0208	0.0208	0.0208
SEN+		416	0.0192	0.0192	0.0192	0.0192	0.0192	0.0192	0.0192	0.0192	0.0192	0.0192
SEN+2		448	0.0179	0.0179	0.0179	0.0179	0.0179	0.0179	0.0179	0.0179	0.0179	0.0179



(a) (b) (c)

Fig. 8: (a) Graphical representation of Reliability values of all SEN MIN for R_{SE}=0.99 to 0.90 for 2×1/1×2, 4×1/1×4 size of MUX/DEMUX and (b) 8×1/1×8 size of MUX/DEMUX and (c) computed RCR values for all SEN MIN.

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