Circuit Design of Clos-based On-Chip Interconnection Networks

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Abstract— Single-hop non-blocking networks have the advantage of providing uniform latency and throughput, which is important for cache-coherent network-on-chip systems. This paper focuses on high performance circuit designs of multi-stage non-blocking networks as alternatives to crossbars. Existing work shows that Benes networks have much lower transistor count and smaller circuit area but longer delay than crossbars. To reduce the timing delay, we propose to design the Clos network built with larger size switches. Using less than half number of stages than the Benes network, the Clos network with 4x4 switches can significantly reduce the timing delay. The circuit designs of both Benes and Clos networks in different sizes are conducted considering two types of implementation of the configurable switch: with NMOS transistors only and full transmission gates (TGs). The layout and simulation results under 45nm technology show that the TG-based implementation demonstrates much better signal integrity than its counterpart. Clos networks achieve average 60% lower timing delay than Benes networks with even smaller area and power consumption.

Keywords— Crossbars; Benes; Clos; Network-on-Chip (NoC); Schematic; Layout.

1. Introduction

Networks-on-Chip (NoCs) have emerged as the key on-chip communication architecture for multiprocessor systems-on-chip and chip multiprocessors [1][27][29]. Achieving scaling performance for future many-core systems will require high-performance, yet energy-efficient on-chip interconnection networks [2][27][28]. Existing NoC topologies can be classified into two categories: (1) Multi-hop interconnection networks, like mesh [4], torus, concentrated mesh [3], etc., (2) Single-hop non-blocking indirect networks, like crossbar [25], Benes [26], Clos [19], etc.

NoC systems, such as the Tiler Tile64 [5], utilize a distributed mesh-based network to avoid the scaling issues of long wires. However, this improved scalability comes at the expense of nonuniform cache access (NUCA) latencies [15] and high variability in memory access latencies [6], as well as increased design complexity to guarantee correctness and fairness. The study in [14] shows that mesh network's accepted throughput at any given node is highly dependent on the location of the destination node, as shown in Fig. 1. A number of solutions have been developed to solve the problem but at the cost of more complexity routing algorithms and adoption of additional buffers at each router. These buffers

consume significant power and area. According to Intel's projections, the interconnection network itself consumes more than 30% of total chip power [16][30].

Fig. 1. Traffic analysis of mesh- and crossbar-based NoC [14].

Contrastingly, single-hop non-blocking networks eliminate the need of intermediate buffers thus can provide uniform latency and throughput, which are very important for cache-coherent many-core systems [14][24]. Additionally, due to their high bisection bandwidth, non-blocking networks can potentially provide lower complexity solutions with quality-of-service guarantees than multi-hop networks [16][25]. The crossbar-based swizzle-switch network (SSN) achieves significant performance improvement in throughput (21%), cache miss latency (3.0x), and energy savings (25%) than the mesh-based network [14].

Our study is focused on high performance circuit designs of on-chip non-blocking networks, including single-stage networks (i.e., crossbar) and multi-stage networks (Benes and Clos networks). The scalability of crossbar designs is limited by the quadratically increased circuit complexity. As an alternative to crossbars, Benes networks have much lower transistor count and smaller circuit area but longer delay than crossbars [17]. In [20], 3D folded designs of Benes networks

This work was supported in part by NSF under grant no. CNS-1126688.

and Clos networks built with 2x2 switches are presented. But there is no exploration of Clos networks with larger size switches. In addition, the aforementioned designs are conducted under 130nm or older technology. There is a need to evaluate these network designs under current newer technology.

To reduce the timing delay, we propose to design the Clos network built with larger size switches. Using less than half number of stages than the Benes network, the Clos network with 4x4 switches can significantly reduce the timing delay. The circuit designs of both Benes and Clos networks in different sizes are conducted considering two types of implementation of the configurable switch: with NMOS transistors only and full transmission gates (TGs). The layout and simulation results under 45nm technology show that Clos networks achieve average significant lower timing delay than Benes networks with even smaller area and power consumption.

The rest of the paper is organized as follows. Section 2 reviews existing work on circuit designs of single-hop non-blocking networks. Section 3 describes the properties of non-blocking networks. Section 4 presents the circuit design methodology. Section 5 presents the simulation results. Section 6 concludes the paper.

2. Related Work

2.1 Crossbar Designs

To provide better bandwidth, Crossbars are used to replace bus-based interconnect fabrics in early multi-core systems, like in the Niagara2 [7] and IBM BlueGene [13]. Crossbar-based architectures not only can provide the uniform memory access latency that is unachievable in multi-stage NoC systems, but also can potentially provide higher bisection bandwidth and lower complexity solutions for quality-of-service guarantees than NoC designs. Despite these advantages, large crossbars are generally considered infeasible because the area and power of traditional matrix-style crossbars grow quadratically with crossbar radix [8]. Therefore, it is commonly believed that they become overly expensive for radices above 32 or 64 [9]. In some work, the crosspoint queueing (CQ) was adopted to replace the traditional input queueing (IQ) to simplify complexity and improve the performance of crossbar scheduling [10]. However, crosspoint queueing was found expensive due to the high partitioning of the switch memory; since there is one memory per crosspoint, the total number of memories grows as $O(N^2)$, which is costly for flow and congestion control algorithms [11][12]. Furthermore, the work in [10] proposed the hierarchically-queued crossbar (HQ) as an organization that lowers memory partitioning. In this organization, an $N \times N$ crossbar is partitioned in $(N/k)^2 k \times k$ sub-crossbars and memories are placed only at the inputs and outputs of the sub-crossbars. Hence, the total number of memories is reduced from $O(N^2)$ to $O(N^2/k)$. Unfortunately, this organization has a major disadvantage: although partitioning is lowered, it remains unacceptably high, especially when N is large. The

reason is that each sub-crossbar has to be relatively small in order to be efficiently scheduled, which, in turn, implies a small k and a quick growth rate of total number of memories.

Existing crossbar circuits mainly adopt MUX-based designs and matrix-based designs [17]. For MUX-based crossbar designs, the latency experienced by a signal depends on crossbar size. For data paths constructed using 2-to-1 multiplexers, doubling the number of inputs results in an additional multiplexer on each line [17]. Pipelined crossbars are proposed to speed up MUX-based designs. Both IBM C64 [18] crossbar and 128x128 crossbar [22] are pipelined MUX-based designs. The IBM Cyclops64 is a 96x96 96-bit-wide crossbar implemented in a 90nm technology, running at 533MHz, and occupying $27mm^2$, including the circuits for queueing, arbitration, and flow control [18]. In [22], a 128x128 32-bit-wide crossbar switch is implemented in 90nm CMOS standard-cell ASIC technology. The crossbar operates at 750MHz and provides a port capacity above 20Gb/s, while fitting in a silicon area as small as $6.6mm^2$ by filling it at 90% level (control not included). Though the throughput is dramatically improved with pipelined crossbar designs, the port-to-port latency is kept undesirable.

The complex wire interleaving in traditional MUX-based crossbars causes the layout challenge at high bus widths [14]. Most recent crossbars use matrix-style structures. The results in [17] show that for the same size crossbar, compared with the MUX-based design, the matrix-based design reduces the transistor count by 90% and latency up to 50%. Conventional matrix-based crossbars consist of the switching fabric and a separate arbiter that configures the crossbar. This decoupled approach imposes the routing challenge and complexity in arbiter design when the radix of the crossbar increases. Passa's work proposed a novel microarchitecture that inverts the locality of wires by orthogonally interleaving the input with the output arbiters, thus reducing the routing area from $O(N^4)$ to $O(N^2 \log^2 N)$. However, the prohibitive overhead of the arbiter (consuming 60% of total crossbar area) still limits the design to scale when implementing high-radix crossbar.

2.2 Benes/Clos Designs

Though matrix-based crossbars overbeat MUX-based designs in both area and timing delay [17], their scalability is still limited by the quadratically increased circuit complexity. As an alternative to crossbars, Benes networks have much lower transistor count and smaller circuit area but longer delay than crossbars [17]. The circuit design of 2D Benes network shows that the Benes network significantly reduces the transistor count and power consumption compared with the same size matrix-based crossbar design. While the latency result of the Benes network is worse than that of the matrix-based crossbar counterpart [17]. In [20], 3D folded designs of Benes networks and Clos networks built with 2x2 switches are presented. The numerical analysis shows that 3D folded design can help improving the latency result. But this work only provides the 3D folded design in theoretical aspect, there is no actual layout of the circuit. As a matter of fact, the TSVs cannot satisfy the density requirement of high-radix crossbar

connection because each TSV needs a large pad area to guarantee the quality. Besides, in this work there is no exploration of Clos networks with larger size switches.

Clos networks have been adopted to interconnect multi/many cores [16][30] in 2D and 3D structures. However, to the best of our knowledge, there is no work on using the Clos network as a replacement of crossbars.

In the literature, the studies on circuit design of crossbar and Benes/Clos networks are limited. Due to the lack of appropriate wire models, it's very inaccurate to conduct circuit level simulation for designs, which completely neglects any effect that physical routing might have on circuit performance. The transistor level simulation might yield important information about the behavior of the actual physical circuits. However, there seems to be few studies based on transistor level simulation of these network circuits although delay boundaries in terms of number of switches and path length have been established.

In [17], the transistor level circuit designs of matrix/MUX-based crossbars and Benes network are accomplished. But from the layout view presented by the author, the following problems are observed: 1) the transistor level layout design is not optimized enough; 2) the maximum size of the design is limited to 16x16, which cannot provide enough results to justify the trend for larger size crossbars. In addition, their aforementioned designs are conducted under 130nm or older technology. There is a need to conduct transistor level circuit designs of these networks under current newer technology.

3. Non-Blocking Networks

The major performance metrics of the circuit designs of non-blocking networks include timing delay, area, and power consumption. The number of stages of a network is the key factor determining the timing delay of the network. Generally, for networks built with the same type of logic units, more stages means longer timing delay. The determining factor of area and power consumption is the transistor count. In this section, we describe the properties of three types of non-blocking networks that are the determining factors of their performance.

3.1 Crossbar

The crossbar is a strictly non-blocking network, i.e., any permutation of inputs and outputs can be realized without confliction. As shown in Fig. 2, each input port is connected to each output port through a dedicated logic unit, which is composed of one *configurable switch*, the basic component used in our circuit design. The number of logic units needed for an $N \times N$ crossbar is N^2 .

The number of stages traversed from one input port to one output port is only one. However, the circuit complexity of crossbars increases quadratically with the crossbar's size. The resulted high power consumption and die area limits the use of crossbars for large-scale NoCs.

Fig. 2. 8x8 Crossbar

Contrastingly, multi-stage non-blocking networks mitigate the complexity in logic units with rearrangeable non-blocking capability.

3.2 Benes Network

An $N \times N$ Benes network basically is built with two symmetrical $N \times N$ butterfly networks. Larger size Benes networks can be built with smaller Benes networks recursively. The basic logic unit is a 2x2 crossbar switch. As shown in Fig. 3.

Fig. 3. Benes network

Base on this recursive nature, the number of logic units used in $N \times N$ Benes network can be derived as:

$$\begin{cases} f(N) = N + 2f(N/2); \\ f(2) = 1; \end{cases} \Rightarrow f(N) = N \log_2 N - \frac{N}{2} \quad (1)$$

Equation(1) shows the amount of logic units used in a Benes network is significantly reduced compared to the amount of logic units used in the same size crossbar.

In Benes networks, the number of stages traversed from an input port to an output port increases as the network size increases. The relation between the number of stages of a Benes network and the network size is derived below.

$$s(N) = 2\log_2^N - 1 \quad (2)$$

Though $O(\log_2^N)$ is a slow increasing function of N , it is desirable to reduce the number of stages.

3.2 Clos Network

To reduce the number of stages for the same size Benes network, we consider Clos networks [22]. A Clos network is composed of three stages of crossbar switches: the input stage, middle stage and the output stage. Each stage is made of a number of same size crossbar switches. A Clos network is defined with a triplet (m, n, r) , where m represents the number of switches at the middle stage, n represents the number of input (resp. output) ports of each switch at the input (resp. output) stage, and r is the number of switches at input/output stages. Each input stage crossbar switch has m outputs, each connecting to one of the middle stage switches.

Based on the definition of the Clos network, Fig. 4 shows the semi-recursive Clos networks built with 4x4 and 2x2 crossbar switches. Fig. 5(a) and (b) show the structures of the two size switches made by crossbar. The number of logic units (i.e., 2x2/4x4 switches) used in such Clos network is derived as:

$$\begin{cases} f(N) = \frac{N}{2} + 4f\left(\frac{N}{4}\right); \\ f(2) = 1, f(4) = 1; \end{cases} \Rightarrow$$

$$f(N) = \begin{cases} \frac{N}{2}(\log_4^N) - \frac{N}{4}; & \text{when } \log_4^N \text{ is an integer} \\ \frac{N}{2}(\log_4^{2N}); & \text{when } \log_4^N \text{ is not an integer} \end{cases} \quad (3)$$

Equation (3) shows the number of logic units needed for Clos networks is much smaller than the number of logic units needed by Benes networks. Notice that in (3), when $\log_4^N$ is not integer, like $N = 8, 32, 128, \dots$, the most middle stage is composed of 2x2 switches. Fig. 4(b) and (d) show this type of Clos network.

The relation between the number of stages of a Clos network and the network size is shown in Equation (4).

$$S(N) = \begin{cases} 2(\log_4^N) - 1; & \text{when } \log_4^N \text{ is an integer} \\ 2(\log_4^{2N}) - 1; & \text{when } \log_4^N \text{ is not an integer} \end{cases} \quad (4)$$

As we can see from Equation (4), for $m = 4$, the number of stages increase 2 every time when the radix of Clos network break through the line of 4^i , and i is an integer. For the example shown in Fig. 4, for (a) and (b) with radix 8x8 and 16x16 respectively, then they have 3 stages for going through the whole Clos network. Once the radix break s through 16 which is 4^2 , as shown in (c), then the Clos has 5 stages.

Fig. 4. Clos network

3.4 Comparison of Clos and Benes Networks

Comparing Equations (1) and (3), the number of logic units of Clos networks is about half of the number of logic units used in Benes networks. Notice that the logic unit represents different size crossbar switches in these two networks. As shown in Fig. 5(a) and (b), the 2x2 crossbar is made of 4 configurable switches, while the 4x4 crossbar is made of 16 configurable switches. Table 1 lists the number of logic units and configurable switches for different sized Benes and Clos networks.

Table 1 Number of logic units and configurable switches for Benes and Clos networks

Size	Clos		Benes	
	Num of logic units	Num of configurable switches	Num of logic units	Num of configurable switches
4x4	1	16	6	24
8x8	8	80	20	80
16x16	12	192	56	224
32x32	48	576	144	576
64x64	80	1280	352	1408
128x128	256	3328	832	3328
256x256	448	7168	1920	7680

Table 2 Number of Stages for Benes and Clos networks

Size	Clos	Benes
4×4	1	3
8×8	3	7
16×16	3	9
32×32	5	11
64×64	5	13
128×128	7	15
256×256	7	17

Equations (2) and (4) show the number of stages needed is reduced from $O(\log_2^N)$ in Benes networks to $O(\log_4^N)$ in Clos networks, when N gets larger, this difference is more significant as shown in Table 2.

Fig. 5. 2x2 and 4x4 crossbar switches

As we know, the number of stages traversed by a signal is the determining factor of the timing delay. For both 2x2 and 4x4 crossbar switches, as shown in Fig. 5, only one logic unit will be passed through from an input to an output. The timing delay for the two crossbar switches should be similar. As such, the total delay experienced from an input port to an output port in Clos shall be much smaller than that in the same size Benes network.

4. Circuit Design of Benes and Clos Network

4.1 Design Flow

The circuits of different sized Benes and Clos networks are designed and simulated through the Cadence design flow, provided by their IC design tools. Circuit level layout and simulations are conducted using Cadence Virtuoso under TSMC 45nm technology. The performance metrics to be compared include critical path timing delay, area, and power consumption.

Fig. 6 illustrates the design flow, which consists of three major steps: schematic design, circuit layout, and simulation. For each specific size Benes/Clos network, the schematic circuit is designed first. After the functional verification for schematic circuit is passed, the layout for each network circuit is drawn based on the schematic circuit. During the layout design period, the DRC checking need be done repeatedly in order to avoid any DRC rule violation.

After the layout is completed without any DRC violation, the net list with parasitic parameters is extracted from layout.

The LVS checking is to ensure the exact matching of the net lists generated by the schematic circuit and the layout circuit.

Fig. 6. Design flow

The final step is to simulate the circuits. First the simulation platform need be built using “config” view in Virtuoso. Then the tools embedded in Virtuoso are used to simulate the circuit and generate the timing delay and power consumption.

4.2 Design of Logic Unit

As described in Section 2, the logic unit of a Benes/Clos network is made of 4 or 16 configurable switches. We consider two alternative designs for the basic configurable switch: 1) single NMOS transistor and 2) full transmission gate which uses two transistors (one NMOS and one PMOS).

Fig. 7. NMOS-based 2x2 crossbar

Fig. 7(a) and Fig. 8(a) show the schematic diagrams of the two designs of the logic unit of 2x2 crossbar. The number of transistors needed by the first design and the second design is 6 and 16 respectively. But the NMOS transistor has its intrinsic defect known as the “weak 1” problem. The signal passes through the NMOS transistor cannot reach the VDD voltage without the help of a buffer. The transmission gate design uses the complementary manner to control the two transistors turn on or off as shown in Fig. 8.

Both transistors are either on or off at the same time to pass or block the signal. When the input signal is '1' ('0'), the PMOS transistor will compensate the weak '1' ('0') from the NMOS transistor.

Our experiment shows that under the TSMC 45nm technology, after the signal passes through the first NMOS transistor stage, the strength of the signal can only reach 75% of the original voltage VDD. In order to solve this problem, buffers are added between every two adjacent stages so that the signal strength of all inputs for next stage is kept at VDD, as shown in Fig. 7(a) and (b). The buffers combined with slow rising of signal coming out from the NMOS transistor introduce significant delay for the signal path.

Fig. 8. TG-Based 2x2 Crossbar

4.3 Schematic and layout Designs

Based on the logic unit design, the schematic circuits of Benes networks are built recursively from 4x4 to 64x64 following Fig. 2. Both schematic and layout circuits are laid out manually. In this work, we have completed the layout of NMOS-based Benes networks to 32x32 and TG-based Benes networks to 64x64. The simulation results on timing delay and power consumption are generated.

Fig. 9. Circuits of 64x64 Benes network

Fig. 9 (a) and (b) show the schematic and layout views of TG-based 64x64 Benes network as an example. When the network size is doubled, the Benes network is duplicated and added with two more stages of crossbar switches. As shown in Fig. 9(a), the 64x64 Benes network includes two 32x32 Benes networks and two input/output stages composed of thirty-two 2x2 crossbar switches.

In the similar way, the schematic and layout circuits of 4x4 to 64x64 TG-based Clos networks are laid out manually. Fig. 10 shows the circuits of 64x64 Clos network.

Fig. 10. Circuits of 64x64 Clos network

5. Experimental Results

In this section, we present the simulation results of all Benes and Clos networks obtained from Cadence Virtuoso simulation tools. The performance metrics including timing delay, area and power consumption are reported and analyzed. For timing delay and power consumption metrics, the results are obtained with wire delay model (i.e., RC model).

5.1 Timing Delay

Table 3 and Fig. 11 show the timing delay results of NMOS-based and TG-based Benes networks as well as TG-based Clos networks. The delay result shown is the average of the rising-transition and falling-transition delays. The wire delay has a significant impact to the timing delay. And the impact is bigger for larger size designs. This trend is attributed to factors of longer wires for interconnecting the inner and outer stages and increased wire load. As shown in the first two columns, for the same size Benes network, the delay of NMOS-based Benes network is about 10 times of the delay with its TG-based counterpart. The basic reason has been mentioned in Section 4.2. The rising delay of NMOS

transistors along the signal path contributes the most to total path delay. In the design with TGs, the rising delay problem is eliminated, thus the path delay plummets.

Table 3 Timing delay of Benes and Clos networks

Size (N×N)	Benes (NMOS) (ps)	Benes (TG) (ps)	Clos (TG) (ps)
4x4	1622.83	101.435	13.615
8x8	3131.015	331.545	192.5
16x16	4578.965	625.86	241.84
32x32	7034.66	1232.44	832.84
64x64	N/A	1584.6	920.95

Fig. 11. Timing delay (unit: ps)

The difference of timing delays between Benes and Clos networks is mostly attributed to the difference between the numbers of stages of these two networks. Table 2 shows the number of stages used for specific size networks, 8x8 and 16x16 Clos networks have as the same number of stages as 4x4 Benes networks. As shown in Fig. 11, the timing delay of 16x16 Clos is larger than that of 8x8 Clos, and both delays are higher than the timing delay of 4x4 Benes network. The reason is that though the number of stages is the major factor determining timing delay, the output load also plays an important role in it. The output load of 16x16 Clos is larger than 8x8 Clos, and both are much larger than 4x4 Benes network. This explains the trend of timing results.

5.2 Area

Table 4 and Table 5 show the transistor number and area of Benes and Clos networks. The first two columns show that the area of NMOS-based Benes network is much smaller than that of the corresponding TG-based Benes network. Each TG contains four transistors, which is 4 times of NMOS, as explained in Section 4.2.

Table 4 Number of Transistors used in Benes and Clos networks

Size (N×N)	Benes (NMOS) <i>Num of Trans.</i>	Benes (TG) <i>Num of Trans.</i>	Clos (TG) <i>Num of Trans.</i>
4x4	40	96	64
8x8	176	320	320
16x16	540	896	768
32x32	1464	2304	2304
64x64	3696	5632	5120

Table 5 Area of Benes and Clos networks

Size (N×N)	Benes (NMOS) <i>Area (um²)</i>	Benes (TG) <i>Area (um²)</i>	Clos (TG) <i>Area (um²)</i>
4x4	40.97	75.81	42.56
8x8	154.10	263.05	227.25
16x16	474.42	764.71	624.03
32x32	684.13	1239.2	1125.7
64x64	N/A	3662.8	2954.1

While NMOS-based Benes networks also need adding the inverters (as buffers) between two neighboring stages to reshape the defect signals caused by weak '1' problem. As such, the transistor account of a TG-based Benes network is slightly more than 2 times of its NMOS-based counterpart. The actual area ration between TG- and NMOS-based Benes networks is less than 2:1.

Fig. 12. Number of transistors

Fig. 12 shows the trend described in Table 4, as we can see, the TG-based Benes and Clos consume similar amount of transistors, which is higher than NMOS-based network. As shown in Fig. 13, consistent with the trend of transistor count, the area of NMOS-based Benes network is the smallest among the three designs. The TG-based Clos network has smaller area than TG-based Benes network for all network sizes and the difference is more significant for larger size N . The smaller layout area of Clos networks is attributed to the fact that by using 4x4 crossbars as major building blocks, less interconnects are used and the circuit is more compacted compared with that of Benes networks.

Fig. 13. Area (unit: um²)

5.3 Power Consumption

Table 6 shows the power consumption for these networks. The results with RC model are much higher than without RC model. Similar to timing delay results, the impact of wire delay is getting bigger with the network size increasing. The power consumption of NMOS-based Benes network is higher than the corresponding TG-based Benes network, because the inverters between two neighboring stages consume significant power to compensate the defect signals caused by NMOS transistor's weak '1' problem.

Table 6 Power consumption of Benes and Clos networks

Size (N×N)	Benes (NMOS) (w)	Benes (TG) (w)	Clos (TG) (w)
4x4	1.149E-6	0.9278E-6	2.748E-7
8x8	4.162E-6	2.491E-6	2.084E-6
16x16	8.064E-6	7.954E-6	3.282E-6
32x32	16.23E-6	10.45E-6	8.415E-6
64x64	N/A	32.85E-6	25.7E-6

Fig. 14. Power consumption (unit: w)

Fig. 14 shows that comparing TG-based Benes and Clos networks, the Benes networks consume more power. On one hand, the data signals go through more stages in Benes network than in Clos network, on the other hand, the signals in Clos network have larger output load considering the larger size logic unit. The combined effect is that Clos networks have lower power consumption than Benes networks. The improvement (over 20%) is more significant for larger size N as shown in Fig. 14.

6. Conclusion

This paper is focused on the circuit designs of different sized Benes and Clos networks considering two types of implementations: with NMOS transistors and full transmission gates. All designs are laid out manually and simulated with Cadence tools. The experimental results show that the TG-based Benes networks have much better timing and power performance than NMOS-based counterparts, though more transistor resources are needed in TG-based designs. Clos networks have 60% timing delay reduction than Benes networks with even smaller area and power consumption. This result confirms that Clos network is a better alternative than Benes networks to replace crossbars in large scale networks. One of the future work is to explore the network performance

of Benes/Clos-based NoCs under both synthetic and real life applications.

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