COMPARATIVE PERFORMANCE ANALYSIS OF SELECTED ROUTING ALGORITHMS BY LOAD VARIATION OF 2-DIMENSIONAL MESH TOPOLOGY BASED NETWORK-ON-CHIP

Saliu Mohammed Shaba[1], Muyideen Omuya Momoh[2], Pascal Uchenna Chinedu[3] Wilson Nwankwo[4] and Aliu Daniel[3]
[1]Federal College of Freshwater Fisheries Technology, New Bussa, Nigeria
[2]Faculty of Air Engineering, Air Force Institute of Technology Kaduna, Nigeria
[3]Department of Electrical and Computer Engineering, Edo University Iyamho, Nigeria
[4]Department of Computer Science, Edo University Iyamho, Nigeria
* bigshaba@gmail.com; momuyadeen@gmail.com
Received: January 17, 2021 Accepted: March 12, 2022

Abstract:

Network-on-Chip (NoC) has been proposed as a viable solution to the communication challenges on System-on-Chips (SoCs). As the communication paradigm of SoC, NoCs performance depends mainly on the type of routing algorithm chosen. In this paper different categories of routing algorithms were compared. These include XY routing, OE turn model adaptive routing, DyAD routing and Age-Aware adaptive routing. By varying the load at different Packet Injection Rate (PIR) under random traffic pattern, comparison was conducted using a 4 × 4 mesh topology. The Noxim simulator, a cycle accurate systemC based simulator was employed. The packets were modeled as a Poisson distribution; first-in-first-out (FIFO) input buffer channel with a depth of five (5) flits and a flit size of 32 bits; and a packet size of 3 flits respectively. The simulation time was 10,000 cycles. The findings showed that the XY routing algorithm performed better when the PIR is low. In a similar vein, the DyAD routing and Age-aware algorithms performed better when the load i.e. PIR is high.

Keywords: Adaptive routing, Deterministic routing, Network-on-Chip, Noxim Simulator, Routing Algorithm

Introduction

System-on-Chip (SoC) is a design paradigm in which heterogeneous blocks often called Intellectual Property (IP) cores, IP blocks, Processing Elements (PEs) or virtual components, pre-designed and pre-verified are obtained from internal sources, or third parties, and fabricated on a given single chip (Gabis & Koudil, 2016).. In the state-of-the-art SoC designs, the foremost problem is the interconnection between the components- IP cores (Fig. 1) or PEs (Rekha & Bhavikatti, 2017).. Network-on-Chip (NoC) has been proposed as a viable solution to the communication challenges on SoCs (Benini, & De Micheli,2002 ; Dally & Towles, 2001).

Routing algorithms plays a significant role in the overall network's performance as it determines the path a packet follows from the source PEs to the destination PEs ((Wu *et al.,* 2016 ; Zulkefli *et al.,* 2018). For a classical deterministic routing method such as XY routing, a given packet is transferred from the source PE to the destination PE through a specific predetermined path irrespective of traffic conditions. XY routing is deadlock free and relatively simple to implement with low power consumption (Singh et *al.,*2013; Umoh *et al.*, 2019). However, as the number of nodes or PEs increases, congestion becomes inevitable because of busty and non-uniform traffics therefore; the packet may experience low throughput and high network latency.

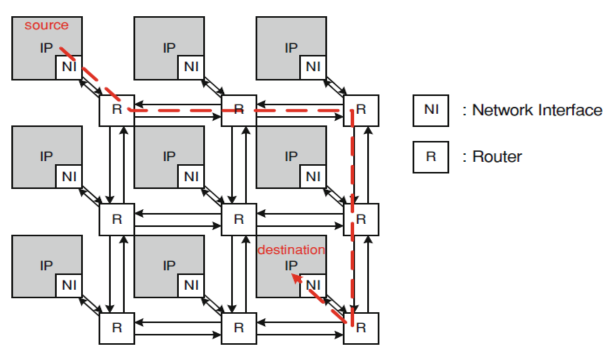

Fig. 1 Network-on-Chip Architecture using Mesh Topology

In an adaptive routing algorithm on the other hand, the path for packet transversal from source to destination is dynamically selected based on the condition of the network thereby avoiding congested regions. Several studies have shown that classical fully adaptive routing algorithm is prone to deadlock without Virtual Channels (VCs) (Charif *et al.*, 2017; Parasar, M & Krishna 2017). Hu and Marculescu (2004) proposed a routing algorithm called DyAD that combine the advantages of both deterministic and adaptive routing algorithms. In DyAD the router works in deterministic mode when there is no congestion in the network and it switches back to adaptive mode when there is congestion in the network. However, the addition of VCs comes with a significant increment in hardware required and complexity in the design of the routers, which potentially brings about increased hardware overhead, power consumption, and network latency (Lee & Huang, 2014). To minimize the aforementioned problems, turn model was proposed (Glass & Ni, 1998).

In the turn model, a turn is a 90^{O} change in the direction of a packet and there can either be clockwise or counterclockwise turn. Therefore, deadlock can be avoided if some turns are prohibited (Glass & Ni, 1998). However, with turn prohibition based on global routing, the adaptiveness becomes highly uneven, some path between the source node and destination node have minimal adaptiveness while the remaining paths are fully adaptive. The performance of NoC may be affected due to this uneven adaptiveness because it limits the ability of the turn model to improve the congestion problem (Chemli & Zitouni, 2015). Towards alleviating this problem, Chiu (2000) proposed a turn model called Odd-Even (OE) turn model that prohibits turns based on the column where the node is located instead of prohibiting certain turns arbitrarily. Additionally, the OE turn model is reported to have more paths to route packets than other turn models (Dahir *et al.,* 2013).
For a conventional OE turn model wherein odd and even columns appear alternatively, the model is limited to a relatively determined path. The conventional RR and other improved RR arbitration technique Liu *et al.,* (2017) typically used in NoC router provides a strong fairness from a single router point of view i.e local fairness. However, since packets traverse several routers on their way to their destination nodes, fairness is basically a global property and as such a mechanism for coordinating the individual routers to allocate output port based on global fairness is required. Consequently, Saliu, *et al.,* (2020) had proposed an Age-aware adaptive routing algorithm with OE turn model that considers the age of a packet as it traverses from source to destination node. With the age-aware adaptive routing, priority is given to the oldest packet in the stream and according to their findings, the algorithm produced better throughput with some traffic patterns including bit reversal and random traffic patterns.
As a key research area in NoC design, different routing algorithms are targeted at different applications hence it is important to evaluate the performance of existing algorithms in a bid to proffer better solution. A comprehensive revision of related works highlighted lack of in-depth analysis with regards to simplicity and inherent freedom from deadlock of routing algorithms (Moraes, 2003.)In this present work different routing algorithm was evaluated for NoCs in a mesh topologies using random traffic pattern to evaluate their performances. Some of the simple and deadlock free routing algorithms include XY, Odd-Even turn model and Age-Aware adaptive routing evaluated in this present work.

2. Routing Algorithms

In this section, two categories of routing algorithms were reviewed. These algorithms were deterministic and adaptive routing algorithms. Under the deterministic category, the XY was considered whereas the OE, DyAD, Age- Aware respectively were discussed under the adaptive algorithms.

2.1 XY Routing

Heman(2000) noted that in XY routing, packets are routed first in the horizontal (X) direction and then in the vertical (Y) direction. This algorithm is deterministic, uses a fixed routing path throughout the process, and is deadlock free as well as livelock free. This algorithm could be implemented for both for regular and irregular network topologies respectively. The XY algorithm is also called dimension order routing (DOR). Here, each node or router of NoC is identified by the (x, y) co-ordinates of that node in a 2D mesh. Accordingly, the data packets move in X-direction first and then in Y-direction towards the destination column. The packets cannot move in Y-direction first. As per turns, eight turns are possible generally, however, the XY algorithm permits 4 of these turns only i.e. West to North, East to South, West to South and East to North. Due to these restrictions, it is deadlock free. In this algorithm, the source router may be denoted by *Cx*, *Cy* whereas the destination router is denoted by *Dx*, *Dy*. The XY algorithm is as follows:

```
XY(Cx,Cy,Dx,Dy)
{

Get Initial directions;
if(Dx==Cx&&Dy==Cy)
Return (Cx,Cy);
else if (Dx>Cx)
Route towards East;
else if (Dx<Cx)
Route towards West;
else if (Dy>Cy)
Route towards South;
else
Route towards North;
}// end
```

In the algorithm the source router is compared with the destination router address and if both are equal then destination and source router are the same. If the destination router's x-coordinate address is greater than the source router's x-coordinate address then packets are routed towards east otherwise towards west. If the y-coordinate of the destination router address is greater than the current router y-coordinate address then packets are routed towards south otherwise towards north (Dally & Towles, 2001)

2.2 Odd-Even Routing

Here, more than one routing path can exist between source and destination node in this adaptive routing algorithm. Accordingly, one path is often selected for routing and the path chosen depends on the network congestion conditions. The OE algorithm is a distributed adaptive routing algorithm, which is based on the odd-even turn model. This model does not need any virtual channel in 2D mesh topology (Cheng & Mak, 2011). In this algorithm, if the x dimension is even then that column is considered even and odd if the column's x co-ordinate is an odd number. This algorithm proposes two theorems, which must be satisfied to avoid deadlocks.

Theorem 1: If a node is present on an even column the packets can't take East to North turns and if a node is present on an odd column the packets can't take North to West turns.

Theorem 2: If a node is present on an even column the packets can't take East to South turns and if a node is present on an odd column the packets can't take South to West turns. The summarized algorithm of the OE routing model is shown below:

```
Get initial directions;
int Ex=Dx-Cx;
intEy=-(Dy-Cy);
if(Ex==0)
{

If(Ey>0)
Route towards North;
Else
Route towards South;
}
Else

{ If(Ex>0)
{ If(Ey==0
Route towards East;
Else
{if((Cx%2==1) ||
(Cx==Sx))
{If(Ey>0)
Route to North;
Else
Route to South
}
}
}
}
Return directions;
} // end
```

2.3 DyAD Routing

DyAD stands for Dynamically Adaptive and Deterministic (Hu & Marculescu, 2004). The DyAD routing algorithm is dynamic in nature in the sense that its operation is automatically adjusted based on the network traffic congestion. On the other hand, the traffic congestion threshold value depends upon user activities on the network. This algorithm uses two types of routing techniques: adaptive and deterministic. Each technique is designed to offer some advantages under particular situation. Deterministic routers work well when the packet injection rate (PIR) is low whereas if PIR increases, adaptive routing works well and gives good throughput. This is one kind of smart or intelligent routing algorithm (Hu & Marculescu, 2004). Thus, in the DyAD routing, congested links are avoided by following other routing paths resulting in higher network throughput desired for NoC applications. It is free from deadlock and livelock due to mixed deterministic and adaptive routing modes into the same NoC. The algorithm for DyAD is as follows:

Algorithm DyAD (Cx,Cy,Dx,Dy)
{Get initial directions;
If (Congestion = 0)
then
Deterministic routing algorithm (XY Routing) Else
Adaptive routing algorithm (OE Routing) Return directions;
} // end

2.4 Age-Aware Adaptive Routing Technique

The routing efficiency of NoC is dependent on the efficiency of the port selection technique employed on the router (Ascia *et al.,* 2008; Aliu & Momoh, 2021). The port selection technique includes input-selection technique and output-selection technique. The technique employed for output-selection determines the output port that the flit is delivered. Input-selection technique on the other hand selects one of the input channels to be granted access to a given output port. For example, flit *fo* of input_0 and flit f1 of input_1 requesting output_1 the same time.

Two types of input-selection techniques mostly used in NoC architecture are First-Come-First-Served (FCFS) and RR input-selection arbitration techniques. Both techniques do not consider priority of the flits as one of the input ports is granted access to a given output port. Each of the aforementioned arbitration techniques is fair to each input port but the fairness is only limited from the perspective of the local ports. Notably, the flit might have encountered some contention against network resources on its path from source to destination and it is possible it might it did seek prioritization while competing for network resources at a given port which if granted could have helped improve the overall global fairness of the network (Saliu, *et al.,* 2020).

3. Methodology

Some notable routing algorithms may need to be critically investigated not only to appreciate their inherent strengths in relation to network throughput but also to discover whether there be some gaps that may require redesign to enhance their features and thus widen their applicability. Primarily, in this paper, three different routing algorithms were compared by evaluating their performances at different Packet Injection Rate using the Noxim simulator. The selected algorithms were: XY routing, OE turn model adaptive routing, DyAD routing and Age-Aware adaptive routing.

In furtherance to strengthening the existing efforts toward improving the global fairness and the overall network performance, this research thereafter, proposes a comparative study of an age-aware adaptive routing with OE turn model to some selected routing algorithms through simulation. Age-aware adaptive routing is a hybridized model that implements an output-selection technique using alterable priority arbitration technique – an improved RR by Liu *et al.,* (2017) and an age-based arbitration technique for the input-selection technique. For the age-based arbitration technique, if more than one input port attempts to access an output port, the arbitration technique compares the ages of flits vying for the same output port. The arbiter then selects the input port whose packet has stayed longest in the network. In a situation where two or more packets exhibit same age, the arbiter randomly selects one of the competing input ports. The algorithm for the age-based arbitration technique was first demonstrated by (Saliu, *et al.*, 2020). The approach adopted in this paper builds Saliu, *et al.,* (2020)'s algorithm to produce an enhanced algorithm as presented below. This algorithm provides the basis for the simulation that follows.

Algorithm: Age-Based arbitration Technique
for (;;) {

CL = no. of access request to jth output channel
for (*channel = i; channel < MAX_CHANNELS; channel* ++)
{ = no. of access request to jth output channel
AGE_1= no. of lost contentions
M_1 = AGE_1;
}
for each *competition in competitions* **do (;;) {**
if $M_1 > M_{1,} M_k$,... **then**
output channel granted to channel *i*
AGE_1 = 0;
increment age of $M_{1,} M_k$,...
if $M_1 == M_{1,}$ then
if $AGE_1 > AGE_1$then
i
grant the access to **channel *i*;**
AGE_1 = 0;
increment age of M_1, M_k,...
else if $AGE_1 < AGE_1$ then

```
0;
grant the access to channel j;
0;
AGE_1 = 0;
increment age of M_1, M_k,...
else
0;
grant the access to random channel WINNER
0;
AGE_WINNER = 0;
increment age of other channels;
end
0;
}
0;
```

Simulation setup

To evaluate the performance of the chosen routing algorithms an improved cycle-accurate NoC simulator Noxim was used. The Noxim simulator is based on System C of Electric System Level (ESL). The NoC configuration parameters used for the simulation is listed in Table 1

Table 1: NoC configuration parameter for the simulation

Parameter	Value
Network topology	4x4 Mesh
Flit width	32 bits
Buffer size	5 flits
Packet size	3 flits
Switching technique	Wormhole switching
Routing technique	Age-aware adaptive routing, XY, OE ,DyAD
Traffic pattern	Random traffic
Packet inter-arrival	Poisson distribution
Packet injection rate	0.1 to 0.45 step 0.05

4. Results and Discussion

The performance of each routing algorithm was analyzed at different loads varied by steadily increasing the PIR in a 4X4 2D mesh. The two important performance metrics of average latency and throughput were evaluated. The average latency was computed as the average time it takes flits to reach their destination nodes. The computed time spans through the creation time, the queuing time at source nodes and the traversal time. The throughput on the other hand would measure the fraction of the maximum load a network is capable of handling. The formula for the average latency and throughput is expressed in equations 1 and 2 respectively (Ascia *et al.*, 2008).

$$Throughput = \frac{Total\ received\ flits}{Number\ of\ nodes \times Total\ cycles}$$

(1)

$$T_{average} = \frac{1}{K}\sum_{i=1}^{K} L_i$$

(2)

The spatial distribution of packets delivered from source node to destination nodes in the network is determined by the traffic patterns, random, transpose 1, transpose 2 and bit reversal traffic patterns are supported by Noxim simulator (Catania *et al.*, 2015).. In random traffic pattern, packets are sent by each router to other routers in a random manner. The pair of source and destination nodes are also selected randomly. With source node (i,j) distributed onto the entire network, the performance metrics of routing algorithms were simulated, recorded, and plotted.

Simulation Results

The simulation results are shown in Table 2-3, Fig2 and 3 respectively. The PIR was varied from 0.1 to 0.45 and the corresponding average latency and throughput were observed and plotted. The packet latencies of XY routing, OE turn model adaptive routing, DyAD routing and Age-Aware adaptive routing are shown in Fig 2 using random traffic pattern, with a packet size of 3 flits in a 4X4 2D mesh topology. It could be observed from Fig 2 that at low PIR, the XY routing performs slightly better than OE turn model, DyAD routing and Age-aware adaptive routing in terms of time taken for the flits to be delivered form source node to the destination node as indicated by lower average latency of XY routing algorithm. However, at medium and higher packet injection rates, an improved performance in terms of average latency was observed as in Fig 2 for DyAD routing and Age-aware adaptive routing. This might be due to the switching between modes due to level of contention in the network and packet age-based arbitration techniques implemented in DyAD routing algorithm and age-aware adaptive routing respectively. The age-aware adaptive routing slightly outperforms DyAD routing algorithm overall. The throughput of XY routing, OE turn model adaptive routing, DyAD routing and Age-Aware adaptive routing is shown in Fig 2 using random traffic pattern, with a packet size of 3 flits in a 4X4 2D mesh topology. It could be observed from Fig 3 that the XY routing algorithm performed better than the OE turn model adaptive routing, DyAD routing and Age-Aware adaptive routing at a low PIR which implies that at lower PIR more packets are delivered to the destination nodes when XY deterministic routing algorithm is employed. Accordingly, as more packets are injected into the network, the OE turn model adaptive routing, DyAD routing algorithm and age-aware adaptive routing has an improved throughput. This is in agreement with the work of (Soni, and Deshmukh, (2015).which stated that partially adaptive routing is good when the PIR is moderate

Table 2. Average Latency at different PIR for some selected routing algorithm

S/ No.	PIR(Packet/Cycle/Node)	XY	OE	DyAD	Age Aware
1	0.1	11.01	14.53	13.92	14.85
2	0.15	12.1	16.21	16.07	16.62
3	0.2	19.09	19.33	19.23	19.47
4	0.25	21.25	21.41	20.66	20.1
5	0.3	25.09	26.33	24.75	24.9
6	0.35	28.92	28.5	28.12	27
7	0.4	31.52	30.4	29.43	27.99
8	0.45	33.76	31.62	30.24	29.82

Table 3. Throughput at different PIR for some selected routing algorithm

S/ No.	PIR(Packet/ Cycle/ Node)	XY	OE	DyAD	Age Aware
1	0.1	0.054	0.040	0.047	0.048
2	0.15	0.098	0.096	0.091	0.091
3	0.2	0.229	0.199	0.201	0.21
4	0.25	0.330	0.220	0.320	0.32
5	0.3	0.3610	0.399	0.381	0.38
6	0.35	0.350	0.362	0.348	0.375
7	0.4	0.340	0.377	0.330	0.369
8	0.45	0.397	0.369	0.310	0.359

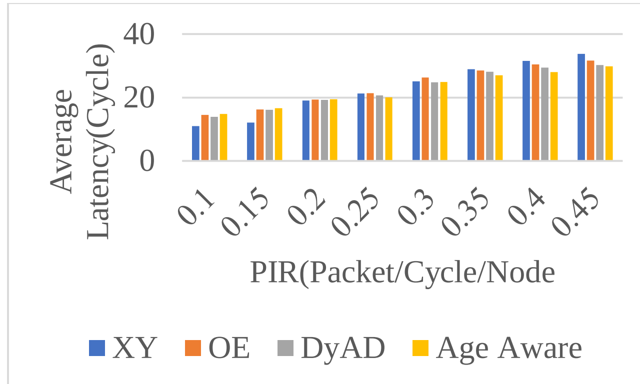

Fig 2: Average Latency at different PIR for some selected routing algorithm

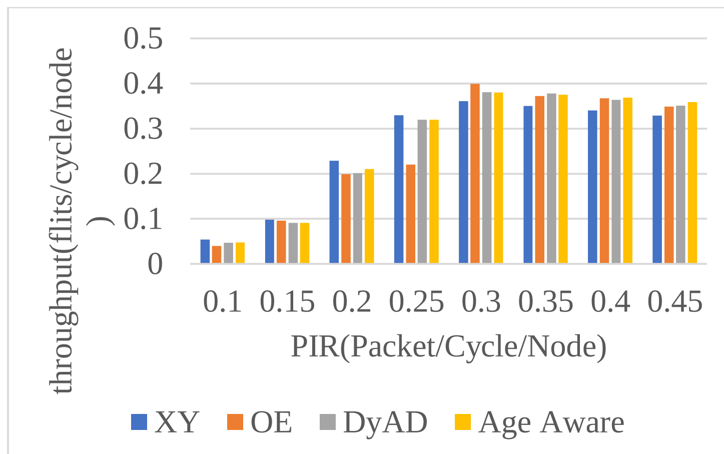

Fig 3: Throughput at different PIR for some selected routing algorithm

5. Conclusion

In this paper, the average latency and throughput of selected algorithms: XY routing, OE turn model adaptive routing, DyAD routing and Age-Aware adaptive routing were compared using simulation. It was discovered that the time taken by packets to be delivered using the XY routing algorithm is lower at a lower PIR than in the OE turn model adaptive routing, DyAD routing and Age-Aware adaptive routing respectively. Nonetheless, at a higher PIR the age-aware adaptive outperforms all other routing algorithms. Similarly, at low PIR, the throughput of

XY routing is higher as packets are delivered to the destination nodes and as PIR steadily increases, the performance of DyAD and Age-Aware adaptive routing improved. The age-aware adaptive routing exhibits a higher performance at moderate PIR i.e. when there is medium network congestion. Conclusively, both DyAD and Age-Aware routing are considered suitable at high PIR i.e. on congested networks but not for a lower PIR network. Consequently, at a low PIR the XY routing and the OE turn model adaptive routing performs better in terms of throughput and latency when compared to Age-aware adaptive routing and DyAD routing The combination of these two algorithms may bring about optimum network throughput irrespective of any prevailing network congestion.

References

Ascia, G., Catania, V., Palesi, M., & Patti, D. (2008).Implementation and Analysis of a New Selection Strategy for Adaptive Routing in Networks-on-Chip, *57*(6), 809–820.

Aliu, D., & Momoh M. O (2021) Optimal Resource Scheduling Algorithm for OFDMA-based Multicast Traffic Delivery over WIMAX Networks using Particle Swarm Optimization International Journal of Software Engineering & Computer Systems, 7 (1), 50-63

Benini, L., & De Micheli, G. (2002). Networks on chips: A new SoC paradigm. *Computer*, *35*(1), 70–78.

Catania, V., Mineo, A., Monteleone, S., Palesi, M., & Patti, D. (2015). Noxim : An Open, Extensible and Cycle-accurate Network on Chip Simulator, 162–163.

Charif, A., Coelho, A., Zergainoh, N.-E., & Nicolaidis, M. (2017). MINI-ESPADA: A low-cost fully adaptive routing mechanism for Networks-on-Chips. In *2017 18th IEEE Latin American Test Symposium (LATS)* (pp. 1–4). IEEE.

Chemli, B., & Zitouni, A. (2015). Design of a Network on Chip router based on turn model. In *2015 16th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering (STA)* (pp. 85–88). IEEE.

Cheng PYK, Mak T (2011) Adaptive routing in network-on-chips using a dynamic programming network. IEEE Trans Ind Electron 58(8):3701– 3716

Chiu, G.-M. (2000). The odd-even turn model for adaptive routing. *IEEE Transactions on Parallel and Distributed Systems*, *11*(7), 729–738

Dahir, N., Yakovlev, A., Al-Dujaily, R., & Mak, T. (2013). Highly adaptive and deadlock-free routing for three-dimensional networks-on-chip. *IET Computers & Digital Techniques*, *7*(6), 255–263.

Dally, W. J., & Towles, B. (2001). Route packets, not wires: on-chip interconnection networks. *Proceedings of the 38th Design Automation Conference (IEEE Cat. No.01CH37232)*,684–689

Gabis, A. B., & Koudil, M. (2016). NoC routing protocols–objective-based classification. *Journal of Systems Architecture*, *66*, 14–32.

Glass, C. J., & Ni, L. M. (1998). The turn model for adaptive routing. In *25 years of the international symposia on Computer architecture (selected papers) - ISCA '98* (pp.441–450). New York, New York, USA: ACM Press.

Hemani A, Jantsch A, Kumar S, Postula A, Oberg J, Millberg M et al (2000) Network on a chip: an architecture for billion transistor era. In: Proceedings of the IEEE NorChip, p 332

Hu J, Marculescu R (2004) DyAD: smart routing for networks-on-chip. In: Proceedings of the41st design automation conference, pp 260–263

Lee, T.-Y., & Huang, C.-H. (2014). Design of Smart Power-Saving Architecture for Network on Chip. *VLSI Design*, *2014*, 1–10.

Liu, L., Zhu, Z., Zhou, D., & Yang, Y. (2017). A fair arbitration for Network-on-Chip routing with odd-even turn model. *Microelectronics Journal*, *64*(March), 1–8.

Moraes, F. G.; Calazans, N.; Mello, A.; Möller, L.; Ost, L. HERMES: an Infrastructure for Low Area Overhead Packet-switching Networks on Chip. Integration VLSI Journal, 2003 (accepted for publication).

Nain, Z., Ali, R., Anjum, S., Afzal, M. K., & Kim, S. W. (2020). A Network Adaptive Fault-Tolerant Routing Algorithm for Demanding Latency and Throughput Applications of Network-on-a-Chip Designs. *Electronics*, *9*(7), 1076.

Parasar, M., & Krishna, T. (2017). Lightweight Emulation of Virtual Channels using Swaps. In *Proceedings of the 10th International Workshop on Network on Chip Architectures - NoCArc'17* (pp. 1–6). New York, New York, USA: ACM Press.

Rekha, S., & Bhavikatti, A. M. (2017). Analysis and Design of Novel Secured NoC for High Speed Communications. *Indian Journal of Science and Technology*, *10*(4).

Saliu, S. M., Umoh, I. J., Sadiq, B. O., & Momoh, M.O. (2020). Age-aware Adaptive Routing for Network- on-Chip Routing with Odd-Even Turn Model. *International Journal of Electrical Engineering and Computing*, *4*(2), 135-140.

Singh, J. K., Swain, A. K., Kamal Reddy, T. N., & Mahapatra, K. K. (2013). Performance evalulation of different routing algorithms in Network on Chip. In *2013 IEEE Asia Pacific Conference on Postgraduate Research in Microelectronics and Electronics (PrimeAsia)* (pp.180–185). IEEE.

Soni, N., &Deshmukh, K. (2015). Comparison Between Three Different Types of Routing Algorithms of Network on Chip. In *Advances in Optical Science and Engineering* (pp. 447-459). Springer, New Delhi.

Umoh, I. J., Marufat, G. O., Basira, Y., Abdulfatai, A. D., &Muyideen, M. O. (2019). BANM: A Distributed Network Manager Framework for Software Defined Network-On-Chip (SDNoC). *Covenant Journal of Informatics and Communication Technology*, *7*(2).

Wu, Y., Lu, C., & Chen, Y. (2016). A survey of routing algorithm for mesh Network-on-Chip.*Frontiers of Computer Science*, *10*(4), 591–601. https://doi.org/10.1007/s11704-016- 5431-8

Zulkefli, F. W., Ehkan, P., Warip, M. N. M., & Phing, N. Y. (2018). A Comparative Reviewof Adaptive Routing Approach for Network-on- Chip Router Architecture. In F. Saeed, N. Gazem, S. Patnaik, A. S. Saed Balaid, & F. Mohammed (Eds.), *Recent Trends in Information and Communication Technology* (Vol. 5). Cham: Springer International Publishing.