

## **A STUDY ON NETWORK ON CHIP [NOC]**

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### **ABSTRACT**

*The growing demands in the faster computation systems has led to having more interfaces with multiple processing units. Bus based systems are found to be slow when dealing with a multi-core processing system. This growing number of processing cores on a chip requires an efficient and scalable communication structure such as Network on Chip (NoC). In this paper, we look into drawbacks of bus based architecture and how NoC's can be faster. Parallelism is one the key for having faster system hence various network topologies are studied. Torus topology is found to be best but, has additional area overhead and more delay due to global routing [10]. Further, we discuss on routing method with Dimension Order Routing (DOR). The major traffic patterns in the network are analyzed with X-Y routing algorithm.*

***Index Terms**— Network on Chip (NoC), multicore system, Torus topology, Dimension order routing, Traffic patterns.*

### **I. INTRODUCTION**

Any electronic system has at least one processing element which is supported by multiple interfaces that are connected to it. Processing element like Microprocessors is considered to be the heart of the system. These processors may not be sufficient when multiple interfaces are connected, hence some co-processors are added into the system to reduce the overhead on the main processor. Now the biggest challenge comes into the picture that is how they will communicate. In the beginning, the systems had very few interfaces and hence all the interfaces were connected to the main processor. Later this was not possible as more interfaces had to be made hence, multiple co- processors were introduced to help the main processor and resource management was the key issues. This gave rise to the bus base architecture systems where the bus is considered to be the main resource and the interfaces along with its processors were connected to this bus. Next challenge was who can use the bus. This led to having a smart control circuit called the bus arbiter who will give access to the bus. Now we had multiple processors which were requesting for the bus, for this a scheduling policy was implemented in the arbiter to choose who should get the bus. The technology is now growing at a rapid rate. Multiple high-end processors are now coming into the market every day. Not just the processors even the interface technology is growing. Now, these interfaces are much faster to support the faster processors. This led to having multiple bus lines in a single system. The faster processors along with some of the subsystems are made to share a single fast bus. The other interfaces like some of the input output devices along with some coprocessors which are slow compared to the main processor are made to share a bus that is slower than that shared by the faster interfaces.

These systems were found to be faster compared to processor centered architecture. But having more subsystems hanging on the same bus still had more delay. The main drawback was that the bus was not configurable. Adding a single subsystem to this bus was complicated and hence architecture was more important. Traditionally, ICs have been designed with dedicated point-to-point connections, with one wire dedicated to each signal. For large designs, in particular, this has several limitations from a physical design viewpoint. The wires occupy much of the area of the chip, and in nanometer CMOS technology, interconnects dominate both performance and dynamic power dissipation, as signal propagation in wires across the chip requires multiple clock cycles. Technology scaling allows, even more, processors and IP blocks to be integrated on a single die, challenging the on-chip communication infrastructure in terms of throughput, scalability and flexibility. To overcome these challenges, NoC has been introduced as an alternative to bus-based interconnection. Network on chip is a communication subsystem on an integrated circuit. Network on chip technology applies networking theory and methods to on-chip communication.

Traditionally networks were made when the Intellectual property (IP) blocks had to communicate with each other or with many other such blocks. These were grouped to form a network where multiple paths were given to the blocks to communicate.

Bus based architecture is found to be very slow compared to the network based design approach. Some disadvantages of the bus based architecture are that the exact number of masters and slaves hanging to it has to be known in prior as delays calculations and timing analysis can be done to analyze its throughput. If more number of masters or slaves are to be connected to the bus then the bus length increases and thus bus becomes slower. The other main disadvantage of the bus is that it will be treated as a resource and can be allocated to any one of the client hence others who need to communicate has to wait till it gives out the bus.

Network based design can avoid delays as there will be many paths to the destination from the source. The routers are one important component in achieving this. A router looks for the destination address and hence directs it to the correct destination. The crossbar is another important component and this help in the communication of multiples IP blocks in the same cycle and hence delays can be reduced.

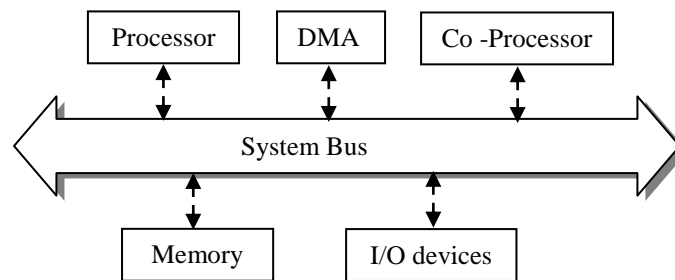
Traffic is another parameter that plays an important role in a network. Many traffic patterns are discussed in many works. Some of them are discussed here and are found to have their own advantages. This paper describes few traffic patterns that are considered in networks configurations. The source to destination paths is decided by routing algorithm. [2]

This paper is divided as follows Section II provides an overview of Bus based system architecture and its disadvantage in parallelism. Section III describes the network topologies. Section IV is about the sub-blocks of NoC. Arbiter, crossbar and router with X-Y routing algorithm is described. In section V briefs on few traffic patterns that are generally used in NoC simulation. Section VI concludes the paper.

## **II. BUS BASED ARCHITECTURE**

A bus based system is one where system bus is considered to be the main resource. A bus based system has a long bus that is shared by many interconnects. In the modern design, these interconnect are referred to as masters and slaves. Master is the one who initializes any traffic and slave is the interface to which the master is

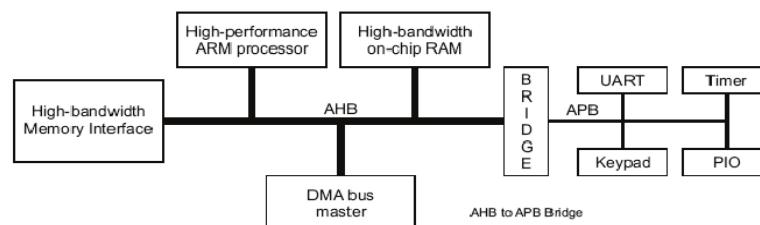
communicating. In general, slaves do not initiate any traffic. A simple bus based architecture is shown in figure 1.



**Figure 1: Single bus based architecture**

The bus based architecture is said to be slower as all the interface connected to it do not work at same clock speed. The bus is thus said to work at the lowest speed interface that is connected to it. Having more interfaces makes the bus to span across the chip. Resistance is directly proportional to the length of the wire and thus resistance also increases. This increase in resistance causes the delay in signal transmission as the delay is proportional to the resistance and capacitance of the transmission line.

To reduce this delay the system bus is normally split into smaller bus and each bus is then connected by a bridging circuit. By doing this the transmission line delay due to RC can be addressed. The interface delays are addressed by having a different bus for interfaces with different speeds. In advance bus architectures like AMBA standards, main processors are connected to the high-speed bus. The speed of the bus is known by its working protocol. In AMBA standard AHB is said to be faster than APB.



**Figure 2: AMBA bus interface**

Hence main processors are connected to AHB and some slower interfaces are connected to APB. A bridging circuit is used to connect this AHB with APB. This is shown in figure 2.

### III. NETWORK TOPOLOGY

Topology is an important parameter of NoC. It is the interconnection of the network; it defines how the network nodes are connected to each other and determine system cost, as well as performance for the network. It has a great impact on the system performance and reliability. Selection of appropriate topology can help to improve the performance of on chip communication.

#### 3.1 Mesh:

In a full mesh network, each network node is connected to every other node in the network. Due to this arrangement of nodes, it becomes possible for a simultaneous transmission of data from one node to several other nodes. [8]

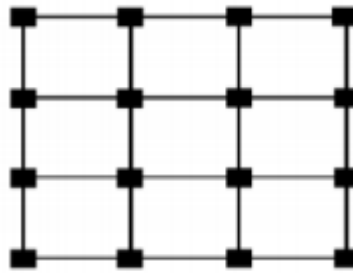


Figure 3: Mesh Network

- Diameter:  $(M+N-2)$
- Bisection Width:  $\min(M,N)$ ,
- Number of Routers required:  $(M \times N)$ ,
- Node Degree: 3(corner), 4(boundary), 5(central).

The nodes of a mesh network require some kind of routing logic so that the data traveling over the network take the shortest path during each of the transmission. Mesh shape network consists  $m$  columns and  $n$  rows and at each intersection, the router is situated and this router is connected to the adjacent router, it is a simple type of topology and easy to implement. 4X4 mesh architecture for NoC is as shown in figure 3. Generally, mesh network has  $M$  rows and  $N$  columns.

### 3.2 Torus:

Torus network is same as mesh, each node is connected to the nearest neighbors, But in torus network, all end node are also connected together. Torus network has better path diversity than mesh network; it has minimal routes to transfer data from source to destination node [10]. Torus architecture for NoC is as shown in figure 4. Torus topology has additional paths as compare to mesh topology to reach the destination. It has also  $M$  rows and  $N$  columns, the parameters of torus network are as follows.[8]

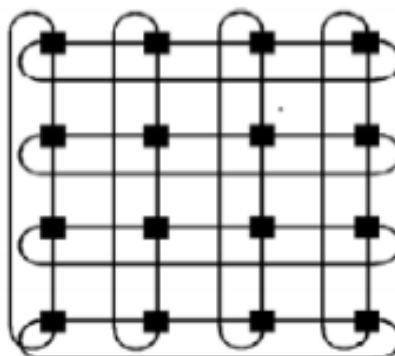


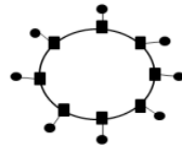
Figure 4: Torus Network

- Diameter:  $\lceil M/2 \rceil + \lceil N/2 \rceil$ ,
- Bisection Width:  $2 \times \min(M,N)$ ,
- No of Routers required:  $(M \times N)$ ,

- Node Degree: 5.

### 3.3 Ring:

In ring Topology, every node in the network is connected to two other nodes and the first and the last nodes are connected to each other. The data that are transmitted over the network pass through each of the nodes in the ring until they reach the destination node. Ring architecture for NoC is as shown in figure 5. [8]



**Figure 5: Ring Topology**

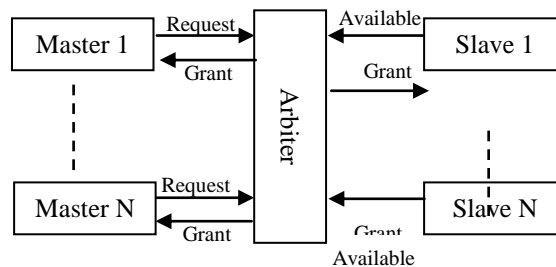
- Diameter: N is even:  $N/2$   
 N is odd:  $(N-1)/2$ .
- Bisection Width: 2
- Node Degree: 2

## IV. SUB-BLOCKS OF NOC

Some important sub-blocks of NoC are Arbiter, Crossbar and Router. A Network on Chip can be achieved by collectively working of these blocks. A network is achieved by connecting different blocks on an IC to a single point called the routers which route to the information to the destination nodes. To do this every flit must have a header containing the destination address. The routers thus look into this headers and route to their destination IPs. A priority based flow control is used to control the grants that are given to a client by the arbiter.

### 4.1 Arbiter

The arbiter controls the arbitration of the ports and resolves contention problem. It keeps the updated status of all the ports and knows which ports are free and which ports are communicating with each other. Packets requesting for same output port are scheduled with priority based arbitration. Suppose at the same time, there are many input ports request the same output or resource, the arbiter gives a grant to any one inputs based on the scheduling algorithm. The arbiter will release the grant on a port which is connected by crossbar once the last packet has finished transmission.



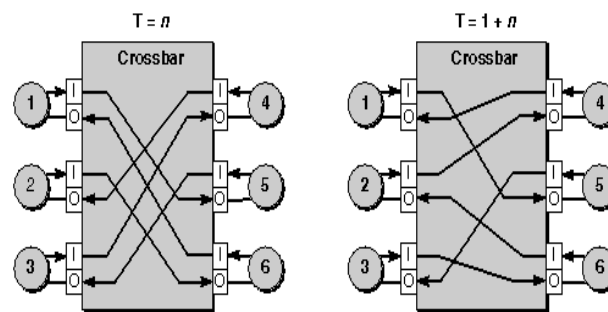
**Figure 6: Block Diagram of Arbiter**

So that other waiting packets could use the output by the arbitration of arbiter. A round - robin arbiter operates on the principle that a request which was just served should have the lowest priority on the next round of arbitration. Depending upon the control logic, arbiter generates a control signal for select lines in a multiplexer based crossbar and read or write signal for FIFO buffer. Contention resolution is an important task of arbiter.

#### 4.2 Crossbar

The crossbar switch is a collection of switches arranged in a matrix configuration. A crossbar switch has multiple input and output lines that form a crossed pattern of interconnecting lines between which a connection may be established by closing a switch located at each intersection, the elements of the matrix. Originally, a crossbar switch consisted literally of crossing metal bars that provided the input and output paths.

A crossbar switch is an assembly of individual switches between a set of inputs and a set of outputs. The switches are arranged in a matrix. If the crossbar switch has  $M$  inputs and  $N$  outputs, then a crossbar has a matrix with  $M \times N$  cross-points or places where the connections cross. At each crosspoint is a switch; when closed, it connects one of the inputs to one of the outputs. The crossbar is a single layer, non-blocking switch. Non-blocking means that other concurrent connections do not prevent connecting other inputs to other outputs. Collections of crossbars can be used to implement multiple layers and blocking switches. A crossbar switching system is also called a coordinate switching system.



**Figure 7: Block Diagram of Crossbar**

Crossbar switches are commonly used in information processing applications such as telephony and circuit switching, but they are also used in applications such as mechanical sorting machines.

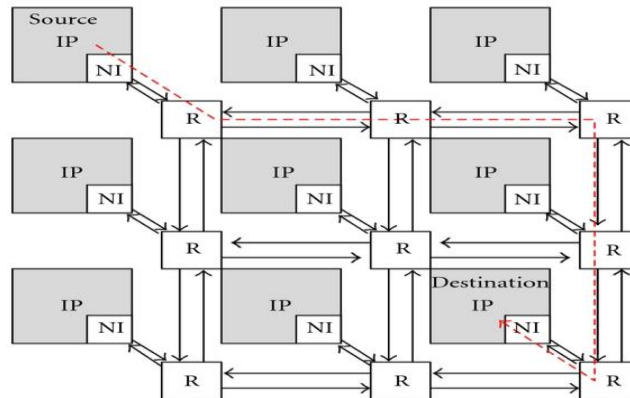
Let us assume that at clock  $T=n$ , the ports independently make the following parallel connections from 1-to-5, 2-to-6, 3-to-4, 4-to-2, 5-to-3, and 6-to-1. Figure 7 shows the source (Input) and target (Output) for each connection, and arrows indicate the direction of flow. When a connection is active, its source and target are not available for any other connection over the crossbar.

At the next clock,  $T=n+1$ , the ports independently reconfigure themselves into six new data links: 1-to-5, 2-to-4, 3-to-6, 4-to-1, 5-to-3 and 6-to-2. At clock intervals, the ports continue making new connections as needed. Connection decisions are based on algorithms that take into account flow control, routing, and arbitration.

#### 4.3 Router

Router plays an important role in NoC. Routing algorithm decides the path for the packet to travel from source to destination. When a packet is sent from a source to a destination, the packet is forwarded hop by hop on the network based on the decision made at each router. For each router, the packet is first received and stored in an

input buffer. Then the control logic in the router is responsible for make routing decision and channel arbitration. Finally, the granted packet travels through a crossbar to the next router and the process repeats until the packet arrives at its destination. The conceptual diagram of a router is as shown in figure 8.



**Figure 8: Block Diagram of Router**

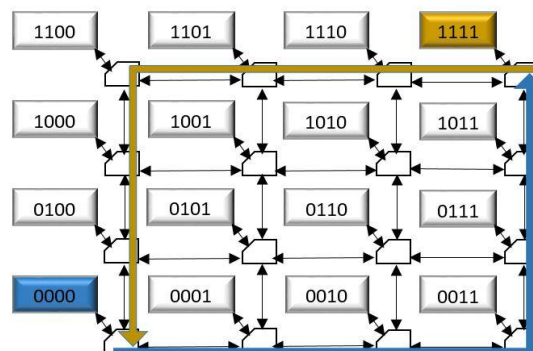
The router has a control logic which describes the switching in the crossbar switch. The control logic has signals coming from the arbiter. the control logic can be a 3-bit as normally crossbar switch has five input ports that can be independently connected to any five output ports.

## V. TRAFFIC PATTERNS

Traffic patterns describe the destination to which the packet is sent by which source. Some patterns describe a specific destination for a specific source. Few patterns describe a different destination to a specific source at a different time. [5] These patterns are thus used to create traffic in NoC. Few of these patterns are described below with dimension order routing (X-Y routing) algorithm.

### 5.1 Bit-Complement

The bit-complement traffic is a simple traffic pattern that is used in the analysis of many networks. This traffic pattern describes a specific destination to a specific source at all time. The destination address is calculated by source address. The address is always a binary value hence the destination is determined by complementing the source address bits.



**Figure 9: Bit-Complement Traffic**

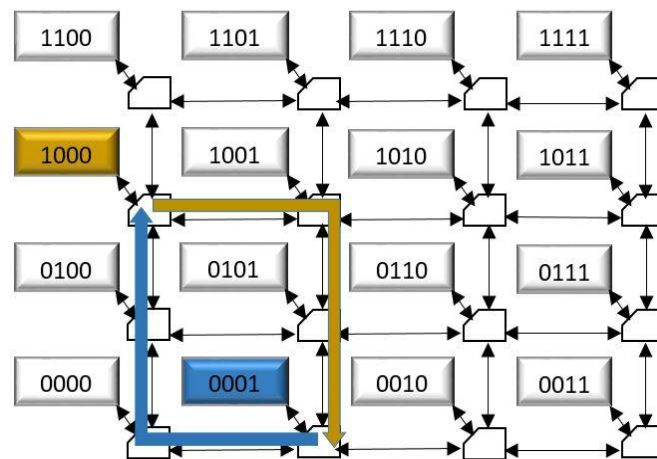
Destination address = complement (Source address)

For source address 0000 the destination is 1111. If we consider dimension order routing algorithm with first X and then Y, then the movement of the packets is as shown in figure 9.

### 5.2 Bit-Reversal

Traffic pattern that is similar to the bit-complement is bit-reversal. The bit-reversal traffic pattern has a dedicated destination to particular source. The destination address can be calculated by changing the first bit as the last bit and second to bit before last bit and so on. That is MSB of the source will be LSB of destination and LSB of the source will be MSB of destination.

Destination address = bit reverse (Source)



**Figure 10: Bit-Reversal Traffic**

For source address 0001 the destination will be 1000. This is shown in figure 10 with X-Y routing algorithm.

### 5.3 Transpose

Transpose traffic is another traffic pattern that is used in many network traffic simulations. This traffic pattern has a specified destination for all the sources. The source address is used to determine the destination address in above two patterns. Here the address of the destination is not calculated by its source address, instead the position of the source is used to define the address of its destination.

Destination address ( $Y^{\text{th}}$  Row,  $X^{\text{th}}$  Column) = Source ( $X^{\text{th}}$  Row,  $Y^{\text{th}}$  Column)

Every interface connected to a router in a network can be described by its position, as the network is considered to be dimensional. Every interface can be thus represented by using the coordinates, which is by its row and column numbers. For source having 0<sup>th</sup> row and 1<sup>st</sup> column. The destination will be 1<sup>st</sup> row and 0<sup>th</sup> Column. The direction of traffic with X-Y routing is as shown in figure 11.



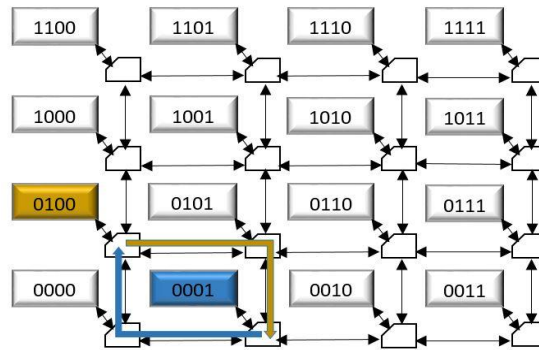


Figure 11: Transpose Traffic

**5.4 Tornado**

Tornado traffic pattern is similar to the transpose traffic. In this traffic pattern, the destination address is obtained by the position of the source. The destination address is calculated by this formula.

$$\text{Destination address} = (K-1)/2 \text{ steps to right and } (K-1)/2 \text{ steps above the source.}$$

In a 4X4 matrix as considered above K=4 hence destination will be one step to right and one step above it. For source as 0001, the destination will be 0110. The path is shown in figure 12 with X-Y routing algorithm.

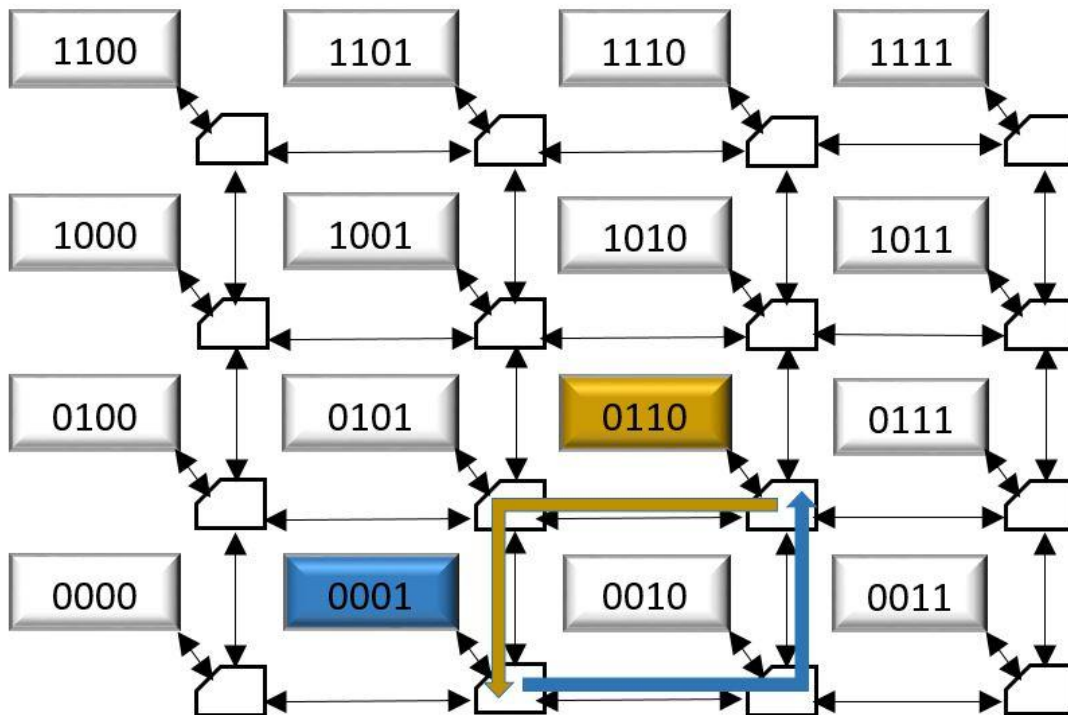
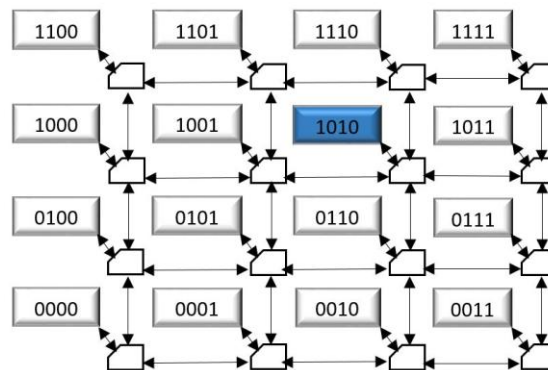


Figure 12: Tornado Traffic

**5.5 Uniform**

The traffic pattern that has different destination address to the same source at different time intervals is the uniform traffic. The traffic is uniform as any source can send packets to any destination. Figure 13, shows the

source which is ready to send the packets of data. The destination is not shown as there is no fixed destination. The destination address will be generated by a random selection of address.

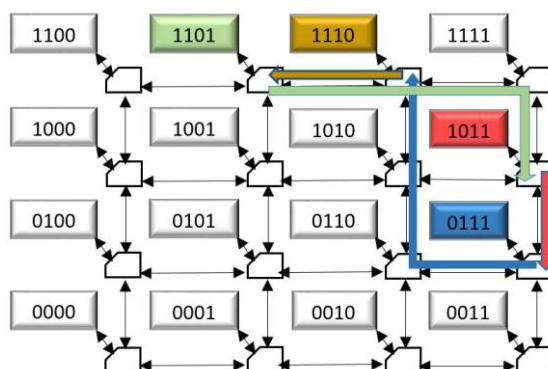


**Figure 13: Uniform Traffic**

**5.6 Shuffle**

A unique traffic pattern that is used in network traffic analysis is the shuffle traffic. Shuffle traffic is not one source to one destination traffic pattern. The shuffle as the name has a shuffled traffic. That is, the traffic pattern is a set of address and destination address is left a circular rotation of its source address. For a 4X4 network shuffle traffic is a set of four address as the minimum bit required to represent these address is 4 bits.

$$\text{Destination address} = \text{Left circular shift (Source address)}$$



**Figure 14: Shuffle Traffic**

Let us assume a starting address as 0111 now this will have a destination as 1110. 1110 will have a destination as 1101 and this will have a destination as 1011. The movement of the traffic with X-Y routing algorithm for shuffle traffic is shown in figure 14.

**VI. CONCLUSION**

A Network on Chip is one of the important block in many multi-core systems. Designing and implementation of NoC's are very important as they describe system performance. Throughput and latency are the important parameters that describe the quality of the NoC. This paper gives an overview of traditional bus based architecture and its disadvantages. NoC's offer much less delay by providing multiple paths to communicate. Arbiter and Router are the important blocks of NoC. Dimension order Routing is considered with X-Y routing algorithm and this algorithm is used to define paths in the traffic patterns.

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