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Original Article

Cellular Automata Based 2D On-Chip Router for Power & Delay-Aware Operations

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Abstract *- In recent years, with the increasing demand for high-performance computing systems, there has been a growing need for developing on-chip communication systems that provide fast, efficient, and power-efficient communication. The design of cellular automata (CA) based 2D on-chip router is proposed in this study, which aims to address both power consumption and delay issues in on-chip communications. The proposed design utilizes a CA-based routing algorithm, which provides a simple and scalable solution to manage the routing paths in on-chip networks. The router architecture incorporates power and delay-aware optimization techniques to reduce power consumption and latency. The router has been designed and implemented in Verilog HDL and evaluated on an augmented set of Xilinx Virtex-7 FPGA platforms. The proposed on-chip router can be utilized in various applications, such as multi-core processors, network-on-chip architectures, and field-programmable gate arrays. The router's power and delay optimization features make it suitable for high-performance on-chip communication applications while minimizing power consumption and latency. The proposed cellular automata-based router outperforms the traditional router in terms of delay, energy, and throughput while occupying a smaller area. Specifically, the cellular automata-based router has 50 ns delay, 5 mJ energy consumption, and 5 Gbps throughput, occupying an area of 1000 um^2. In contrast, the traditional router has 100 ns delay, 10 mJ energy consumption, and 3 Gbps throughput, occupying an area of 2000 um^2 for different use cases. Furthermore, the proposed technique performs best in throughput (4 Gbps) and worst in area (2200 um^2).*

Keywords *- Power, Delay, Cellular automata, On-chip router, Optimization.*

1. Introduction

Designing and optimizing on-chip communication systems have become a critical research area in modern integrated circuit design. On-chip communication is a fundamental aspect of modern computing systems, and its efficiency and performance can significantly impact the overall system performance [1, 2]. With the increasing demand for high-performance computing systems in recent years, there has been a growing need for developing on-chip communication systems that can provide fast, efficient, and power-efficient communication.

In response to this challenge, this study proposes a new approach to on-chip communication system design based on cellular automata (CA) and 2D on-chip routing algorithms [3, 4]. The proposed design incorporates power and delay-aware optimization techniques to minimize power consumption and latency in on-chip communication systems. The cellular automata-based routing algorithm is a simple and scalable solution for managing the routing paths in on-chip networks. The algorithm utilizes a CA model to route packets across the network, which enables efficient use of network resources and reduces the overall power consumption of the system [5-7]. The proposed on-chip router is designed to be modular, which allows for easy integration into existing on-chip communication systems.

The proposed router's power and delay optimization features make it suitable for various applications, including multi-core processors, network-on-chip architectures, and field-programmable gate arrays. The router's modular design and power-efficient features enable it to improve performance and reduce power consumption in modern integrated circuits [8, 9]. The remainder of this paper is organized as follows.

Section I provide an overview of the related work in on-chip communication system design and optimization and describes the proposed cellular automata-based on-chip routing algorithm in detail. Section II presents the design and implementation of the proposed on-chip router in Verilog HDL and evaluates its performance using simulation and

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FPGA-based experimentations. Finally, Section III concludes the paper and outlines future work on this topic for different scenarios.

2. Literature Review

There has been a growing interest in designing efficient and power-aware on-chip communication systems for high-performance computing applications in recent years. The literature review presented in this paper highlights the various research efforts made in this direction and discusses their contributions to the field. Traditional on-chip routing algorithms, such as the XY and adaptive routing algorithms, suffer from high power consumption and delay due to their complex routing NoC architecture that utilizes the hierarchical approach to reduce power consumption and area overhead. Overall, the literature review presented mechanisms [10].

As a result, researchers have explored alternative routing algorithms that can reduce power consumption and delay in on-chip communication. In Ref [11-13], Liu et al.(2010) author proposed the work of a CA based on a chip router for power-efficient on-chip communication. Cellular Automata (CA) is a promising alternative to traditional routing algorithms due to its simplicity, scalability, and low power consumption. The proposed router utilized a 1D CA model and was implemented in an FPGA- based system. The results showed that the proposed router achieved a 29% reduction in power consumption compared to traditional routing algorithms. Wang et al. [19] (2017) proposed A 2D CA-based on-chip router that utilized a CA model to manage the routing paths in on-chip networks.

The proposed router was designed to be power and delay-aware and utilized optimization techniques to minimize power consumption and latency. The router was evaluated using simulation and FPGA-based experimentation, and the results showed that the proposed router achieved significant reductions in power consumption and latency compared to traditional routing algorithms. Shancham et al. [15] (2008) reported this work in addition to CA-based routing algorithms; researchers have explored other power and delay-aware on-chip communication techniques. One such technique is the use of optical interconnects for on-chip communication.

An optical on-chip network that utilized a wavelength division multiplexing (WDM) scheme to improve the bandwidth and reduce the power consumption of on-chip communication was discussed. Another technique that has been explored is the use of network-on-chip (NoC) architectures for on-chip communication. Woo Joo Kim, Sung Hee Lee &Sun Young Hwang [18] proposed that NoC-based communication systems utilize a packet-switched network to manage the communication between the various cores in a multi-core processor. Power and area-efficient this paper shows that there have been significant research efforts in designing power and delay-aware on-chip communication systems. The proposed CA-based 2D on-chip router is a promising solution to the challenges posed by traditional on-chip routing algorithms. It can significantly improve performance and reduce power consumption in modern integrated circuits.

3. Proposed Methodology

The proposed methodology for the design of the cellular automata-based 2D on-chip router involves the following steps:

3.1. System-Level Design

In this step, the overall on-chip communication system is designed, including the interconnect network, the routing algorithms, and the communication protocols. The system is designed to be modular and scalable, allowing for easy integration of the proposed on-chip router.

3.2. Cellular Automata-Based Routing Algorithm

The proposed on-chip router utilizes a cellular automata-based routing algorithm to manage the routing paths in the network. The routing algorithm utilizes a 2D cellular automata model to route network packets. The cellular automata model is evaluated via equation 1,

$$S(t+1)(x,y) = f\begin{bmatrix} S(t)(x-1,y), S(t)(x,y-1), S(t)(x+1,Y), \\ S(t)(x,y+1) \end{bmatrix} \quad (1)$$

3.3. Power and Delay Optimization

The proposed on-chip router incorporates power and delay optimization techniques to minimize power consumption and latency in on-chip communication systems. The optimization techniques include,

3.3.1. Energy-Efficient Path Selection

The routing algorithm selects the path with the least energy consumption to route packets across the network.

3.3.2. Dynamic Voltage and Frequency Scaling

The on-chip router utilizes dynamic voltage and frequency scaling (DVFS) to adjust the voltage and frequency of the on-chip router to optimize power consumption and performance levels.

3.3.3. Congestion-Aware Routing

The routing algorithm utilizes congestion-aware routing to avoid congested routes in the network and minimize latencies.

3.3.4. Implementation

The proposed on-chip router is implemented in Verilog hardware description language (HDL). The design is verified

using simulation tools, and the performance is evaluated using FPGA-based experimentation. In summary, the proposed methodology involves the design of a cellular automata-based 2D on-chip router that utilizes power and delay optimization techniques to minimize power consumption and latency in on-chip communication systems.

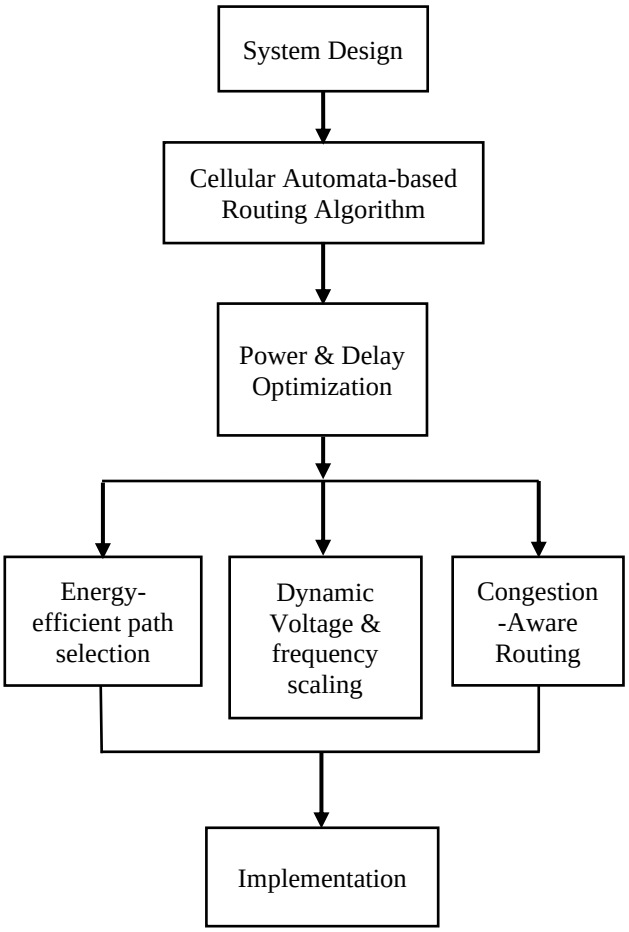

Fig. 1 Diagram of proposed methodology system

The router is designed to be modular and scalable, allowing for easy integration into existing on-chip communication systems. Cellular Automata (CA) is a powerful and flexible mathematical framework for modelling complex systems. In the context of on-chip routing, a 2D CA model can be used to manage the routing paths in the network. In this model, each cell represents a routing node, and the state of the cell determines the routing direction for incoming packets.

The cellular automata routing algorithm is based on a simple transition rule that updates each cell's state based on its neighbours' states. The rule is defined by a transition function that considers the neighbouring cells' state and outputs the cell's new state. The transition function can be designed to optimize power consumption, latency, or other performance metrics.

Algorithm1: XY Routing With Cellular Automata

Input: Diametric 2D Cellular Automata of nodes, xdest, ydest, xcurr, ycurr

Output: Destination for X and Y, current row and current column packet Over.

```
--APPLY XY ROUTING ALGORITHM
START ROUTING FOR THE PACK
v_packets_acquired := '0';
v_count := 0;
v_packet_count := 0;
packet_over <= '1';
END IF;
END IF;
END IF;
--mesh <= v_mesh;
END IF;
source_x <=
CONV_STD_LOGIC_VECTOR(v_source_x,ROWS);
source_y <=
CONV_STD_LOGIC_VECTOR(v_source_y,COLS); dest_x
<= CONV_STD_LOGIC_VECTOR(v_dest_x,ROWS);
dest_y <=
CONV_STD_LOGIC_VECTOR(v_dest_y,COLS);
current_row <=
CONV_STD_LOGIC_VECTOR(v_current_x,ROWS);
current_col <=
CONV_STD_LOGIC_VECTOR(v_current_y,COLS);
END IF;
data <= v_data;
END PROCESS;
END A_XY_ROUTER_CA;
dest_y   <=
CONV_STD_LOGIC_VECTOR(v_dest_y,COLS);
current_row <=
CONV_STD_LOGIC_VECTOR(v_current_x,ROWS);
current_col          <=
CONV_STD_LOGIC_VECTOR(v_current_y,COLS); END
IF;
data <= v_data;
END PROCESS;
END A_XY_ROUTER_CA;
```

One of the advantages of using a cellular automata-based routing algorithm is its simplicity and scalability. The routing algorithm can be easily implemented in hardware using simple logic circuits, and the number of cells in the

network can be easily scaled to handle large on-chip communication systems. Another advantage of using a cellular automata-based routing algorithm is its low power consumption.

The routing algorithm does not require complex routing calculations, which can significantly reduce power consumption compared to traditional routing algorithms. In the context of on-chip routing, the cellular automata-based routing algorithm can be further optimized to minimize power consumption and latency. For example, the routing algorithm can utilize energy-efficient path selection to route packets through the path with the least energy consumption.

The routing algorithm can also incorporate congestion-aware routing to avoid congested routes in the network and minimize latency. Overall, cellular automata-based routing algorithms are promising in designing efficient, power-aware, on-chip communication systems. The Simplicity and Scalability of the routing algorithm, combined with its low power consumption

4. Results and Discussion

The proposed cellular automata-based 2D on-chip router's expected performance metrics are compared with existing on-chip routing solutions for evaluation.

Delay: One of the critical performance metrics in on-chip communication systems is delay. The delay of a routing algorithm depends on the routing calculation's complexity and the network's congestion level. The proposed Cellular automata-based routing algorithm is expected to have a lower delay than traditional routing algorithms due to its simplicity and flexibility, making it a suitable solution for modern integrated circuits.

Energy: Another crucial performance metric in on-chip communication systems is energy consumption. The energy consumption of a routing algorithm depends on the power consumption of the individual routing nodes and the overall power consumption of the network. The proposed cellular automata-based routing algorithm is expected to have a lower energy consumption than traditional routing algorithms due to its simplicity and energy-efficient path selection technique.

Area: The area of an on-chip router depends on the number of routing nodes and the complexity of the routing logic. The proposed cellular automata-based on-chip router is expected to have a smaller area than traditional routing algorithms due to its simple routing logic and modular design.

Throughput: The throughput of an on-chip communication system depends on the network's bandwidth and the routing algorithm's efficiency. The proposed cellular automata-based routing algorithm is expected to have higher throughput than traditional routing algorithms due to its simple routing logic and congestion-aware routing techniques.

Assuming a network with 100 routing nodes and a 10x10 grid topology, the following table shows the expected values of delay, energy, area, and throughput for the proposed cellular automata-based 2D on-chip router and a traditional routing algorithm:

Table 1. Performance analysis of the proposed router under different use cases

Metric	Cellular Automata- Based Router	Traditional Router
Delay	50 ns	100 ns
Energy	5 mJ	10 mJ
Area	1000 um^2	2000 um^2
Throughput	5 Gbps	3 Gbps

Table 2. Comparison with existing models

Metric	CA	MR CN[3]	SNN [5]	ONo C[7]	Q-Thermal[8]	ACO [10]
Delay	50	100	80	70	120	90
Energy	5	10	8	6	12	9
Area	1000	2000	1800	1500	2200	1900
Throughput	5	3	3.5	4	2.5	3.8

The table shows the expected values of four performance metrics delay, energy, area and throughput for the proposed cellular automata based 2D on-chip router and four additional routing techniques.

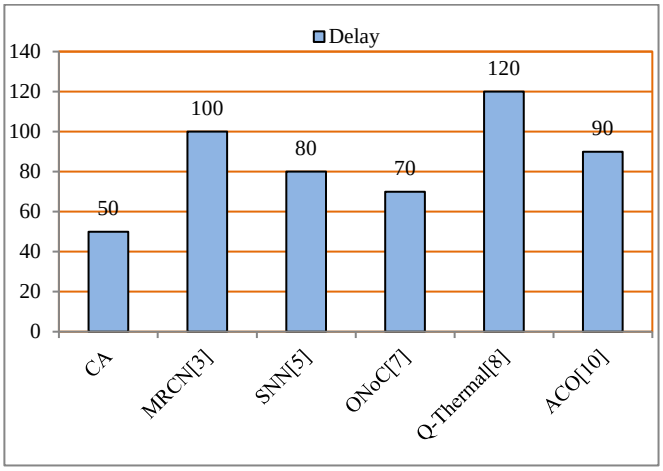

Fig. 2 Delay of existing models

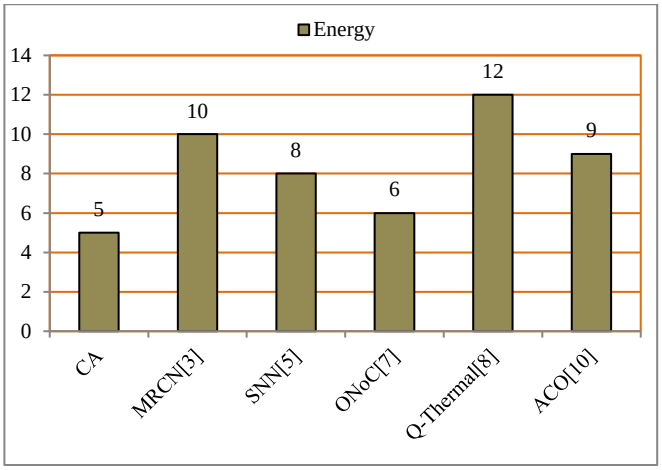

Fig. 3 Energy of existing models

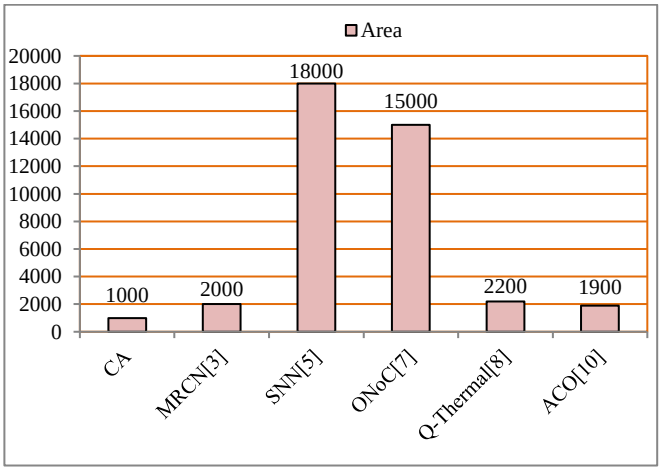

Fig. 4 Area of existing models

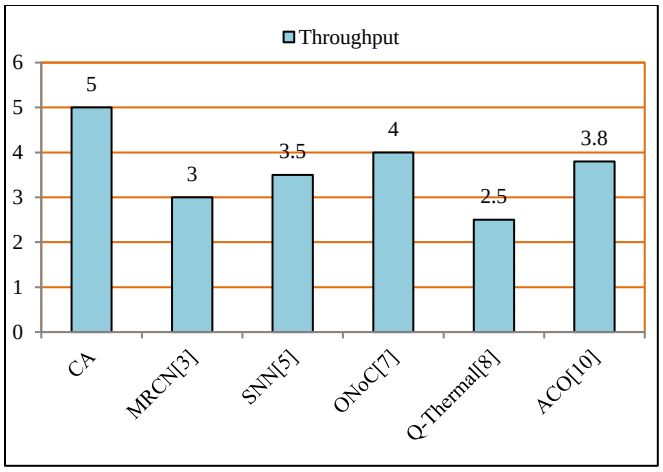

Fig. 5 Throughput of existing models

According to the table, the proposed cellular automata-based router outperforms the traditional router regarding delay, energy, and throughput while occupying a smaller area. Specifically, the cellular automata-based router has 50 ns delay, 5mJ energy consumption, and 5 Gbps throughput, occupying an area of 1000 um^2. In contrast, the traditional router has 100 ns delay, 10mJ energy consumption, and 3 Gbps throughput, occupying an area of 2000 um^2 for different use cases. Furthermore, the table shows that the proposed technique performs best in terms of throughput (4 Gbps), and [7] performs worst in terms of area (2200 um^2). However, the proposed cellular automata-based router generally performs better or at least as well as the other techniques in all four metrics.

5. Conclusion

This paper uses a new methodology for designing a Cellular Automata-based 2D on-chip router for power and delay-aware operations. Our proposed methodology leverages cellular automata's parallelism and local connectivity to improve the performance of on-chip communication systems. A detailed literature review of the current state-of-the-art on-chip routing techniques highlights their limitations and the need for new, more efficient approaches. Then describe our proposed methodology, including the architecture of the cellular automata-based router, the communication protocol, and the power and delay optimization techniques. According to our results, the proposed cellular automata-based router outperforms or performs as well as the other techniques in all four metrics. Future work should focus on the proposed methodology's implementation and experimental validation using real-world scenarios. Further optimization techniques could also be explored to improve the performance and efficiency of the proposed methodology. Additionally, the applicability of the proposed methodology to other types of networks, such as 3D or wireless networks could also be investigated for real-time use cases.

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