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Impact of Virtual Channel, Subnets and Routing Algorithm Effects on WiNoC Performance

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Abstract The Network-on-Chip (NoC) paradigm is a communication network that is used on a chip to facilitate parallel interaction among all cores, thereby enhancing inter-core performance. However, the NoC's ability to improve performance is hindered by high latency and energy dissipation resulting from multi-hop communication over long distances. To address this, Wireless Network-on-Chip (WiNoC) was introduced to improve the efficiency and performance of the system. The efficiency of the WiNoC architecture is dependent on a good choice of virtual channels (VC) allocation for organizing the cores into subnets. By reducing communication latency, adding a wireless router per subnet with a better routing algorithm helps to improve performance. This research examines impact of VC, subnet size, and routing algorithms in WiNoC by tuning the packet injection rate with three traffic distribution, network architectures of the 64, 256, and 1024 cores. Hence, this paper makes two major contributions: firstly, a detailed implementation of a NoC router in terms of VCs (2, 4, and 8), and secondly, a WiNoC with a parameterizable number of VCs along with four subnets (2, 4, 8 and 16). The study evaluates and compares the latency and throughput performance of the four routing algorithms and three traffic distribution patterns in terms of PIR using a cycle-accurate Noxim simulator based on system C. This study showed that virtual channels (VCs) significantly enhance energy consumption in network-on-chip (NoC) architectures, whereas energy consumption in WiNoC architectures is significantly decreased. However, the performance of WiNoC architecture had a noticeable effect by the choice of subnets and routing algorithms.

Keywords Virtual Channel, WiNoC, NoC, Subnet, Routing Algorithm, PIR

1. Introduction

WiNoC technology integrates wireless connectivity into a conventional wire-based NoC architecture. The WiNoC was designed to enhance the performance of the NoC by minimizing energy consumption and latency, and enabling high-bandwidth data transfer in a single hop over long distances [1-4]. The topology of the NoC, which includes the physical layout, network channels, and links between intellectual property (IP) cores, has a significant impact on its performance. The topology selected impacts both the distance between the source and destination IP cores and the number of hops that packets must travel through [5-7]. To achieve efficient packet transmission from source to destination, the routing protocol must select the most effective route for data transfer. To determine the optimum path between a source and a destination, a routing protocol is used. The algorithm is responsible for determining the most effective direction for network traffic within and across various network systems. The placement of wireless connections between specific source and destination hubs is crucial for creating low-power and high-speed interconnections that enhance network performance.

The smaller networks within the system architecture are referred to as subnets and are divided into compact groups of nearby cores. These subnets consist of a reduced number of cores or IPs, which enhances the flexibility in designing their architectures. Like regular NoCs, subnets consist of switches and links, but with the advantage of having a shorter average path length for intra-subnet communication when compared to communication across a single NoC that spans the entire system [9, 10]. The cores were linked to a centralised hub via direct links, and the hubs from all subnetworks were linked in a second-level network to form a hierarchy WiNoC, Subnet, Virtual Channel, Routing Algorithmically structure [11-14]. However, different subnet architectures may be available, such as mesh, star, ring, etc. and mesh topology was used for this study [15].

Although wormhole routing is a viable flow control strategy for NoCs due to its low latency and moderate buffering requirements, non-virtual channel (VC) routing is prone to head-of-line (HoL) blocking, which can severely limit performance. To address this issue, buffer storage can be divided into multiple VCs for each network channel to increase network throughput. Virtual Channel Flow Control (VCFC) is a technique that can enhance network performance by utilizing multiple virtual channels (VCs) for a physical channel [16-18]. The concept of virtual channel was initially introduced to facilitate deadlock-free routing in wormhole switching networks, allowing a single physical channel to be split into multiple virtual channels. Given the typical low-latency and low-buffering requirements of most chips, virtual channel wormhole switching is a suitable switching technique.

This study aims to examine the impact of subnets, virtual channels (VCs), and four routing algorithms on WiNoC performance efficiency through simulations. The study further examines the effects of different packet injection rates on three distinct traffic distributions. Additionally, the study explores the influence of radio hub allocation and placement on the capacity of WiNoC architecture to handle large networks, with a focus on virtual channel and subnet capabilities. The remaining sections are structured as follows: Section II provides relevant background of the study, Section III focuses on the WiNoC architecture and routing algorithms employed in this study. Section IV elaborates on the experimental configuration, describing the setup and parameters used in the simulations, and Section V provides an analysis of the results, including wireless utilization, power consumption, average delay, and throughput variation for different numbers of VCs and subnets against injection rate and traffic pattern. Finally, in Section VI, the paper concludes with suggestions for future work.

2. Related Works

Researchers have developed numerous techniques aimed at improving the efficiency of routing schemes and traffic distribution within WiNoC. In one such effort, authors [18] introduced a novel router architecture that facilitates adaptive virtual channel sharing across different input ports. Their architecture aimed at addressing the underutilization of virtual channels and enhancing power and area consumption performance. Additionally, the authors presented a new router architecture called the 5-port virtual channel router, which incorporates simplified dynamic arbitration mechanisms. This architecture enables deterministic and rational arbitration within the virtual channels. This approach can manage both guaranteed and best-effort traffic. It brings advantages specifically in scenarios where router inputs possess lengthy queues that can be effectively partitioned among virtual channels (VCs). Previous research has consistently demonstrated the benefits of implementing VCs over a single multipurpose (MP) channel, showing improvements in NoC traffic efficiency, as shown in studies [19, 20]. However, these studies do not consider other factors such as subnets, and a small number of used ports are outside the scope of these studies.

In [21], the authors implemented virtual channels in a Hermes NoC. The study reported reduced latency and improved network throughput, demonstrating that VCs could enable higher injection rates in comparison to NoCs that did not incorporate VCs. However, the research was restricted to an 8x8 mesh NoC architecture and did not consider the impact of subnetworks or different mesh architectures. Future research could investigate the performance of VCs in various mesh architectures and examine how they interact with subnetworks to further enhance NoC performance. Similarly, the study in [15] investigated the effects of subnets on NoC performance, specifically examining the impact of different subnet configurations on delays and throughput under varying PIR rates. The study observed that with an increase in the number of IPs, the optimal PIR safe domain shifted towards higher PIR rates and larger subnets. The authors also found that subnet extension significantly improved system performance across different PIR and subnet ranges. However, the study did not take into account the impact of virtual channels and routing algorithms on their findings, thus creating an opportunity for future research to explore the combined impact of subnets, virtual channels, and routing algorithms on the performance of Network-on-Chip (NoC) architecture.

In [22], the study examined the impact of routing algorithms and packet injection rate (PIR) on the effectiveness of systems-on-chip (SoC) communication. The study was conducted using switch-based NoCs and a 16-core mesh topology with a limited number of IP blocks. The study discovered that under a certain injection rate, a network-on-chip (NoC) can encounter packet saturation.

The study evaluated the performance of three routing algorithms, namely fully adaptive, XY, and west first, in terms of packet latency, power consumption, and throughput. Additionally, the study identified the appropriate flow control to manage congestion. Furthermore, multiple studies have investigated the effects of different routing schemes and varying sizes of WiNoC architectures on network traffic distribution, specifically in comparison to conventional NoC mesh. The impact of radio hubs on WiNoC was examined in [23], the study uniformly distributed 4x4 radio hubs throughout the network to evaluate global average delay, energy consumption, wireless utilization and throughput. To conduct their analysis, their work utilized the cycle-accurate Noxim simulator, which allowed for the simulation of various NoC and WiNoC architectures. Different traffic load distributions were considered, and three network sizes (8x8, 16x16, and 32x32) were evaluated. The findings of the study revealed that the WiNoC architecture with a network size of 16x16 exhibited superior average speedup and enhanced network throughputs compared to the other configurations. This observation highlights the potential benefits of the 16x16 WiNoC architecture in terms of enhanced performance and efficient utilization of network resources. However, the study did not factor in the influence of virtual channels (VCs) and subnets on the results, and the radio hub size was restricted to 4×4 only.

3. WiNoC Architecture

WiNoC architecture consists of two layers: a lower layer with wired connections and an upper layer with wireless connections. The WiNoC architecture is designed with two levels of connectivity: firstly, all the IP cores are interconnected in subnets and connected to a central radio hub via traditional wired connections. Secondly, the radio hubs communicate with each other using distributed wireless connections. WiNoC utilizes medium access control (MAC) for efficient communication between its radio hubs, which are equipped with wireless interfaces (WIs) to enable seamless wireless connectivity and facilitate data transmission within the network [7]. The WiNoC architecture is composed of two layers: the wired layer and the wireless layer. The wired layer includes segments of wires, routers, IP cores, and resource network interfaces (RNIs). In contrast, the wireless layer consists of radio hubs that are interconnected using wireless connections. This arrangement is depicted in Figure 1, illustrating the distinct components and connectivity within the WiNoC architecture. The wires and routers are arranged similarly to street grids in a city, with the IP cores or resources positioned on city blocks separated by wires [27]. IP cores incorporated in the WiNoC architecture encompass a variety of components, including general-purpose processors, digital signal processing units, memory, I/O controllers, graphic controllers, and other related elements. Positioned as the upper layer in the NoC architecture, the wireless layer utilizes radio hubs as the primary communication medium for interconnecting nodes. These radio hubs play a vital role in facilitating efficient and effective communication among the various components within the network. This wireless connectivity reduces network latency, particularly for nodes located far apart from each other.

This study employed three different WiNoC architectures (8x8, 16x16, and 32x32), Figure 1 illustrates a generic example of an 8x8 (64 nodes) mesh WiNoC architecture with 4x4 radio hubs and 16 subnets evenly distributed throughout the network, which is a two-level network architecture. The first level in Figure 1 is a classical, traditional wired 8x8 mesh NoC topology. The upper level of the network is a 4x4 wireless network consisting of multiple radio hubs, with each hub having a 4-tile concentration and being shared by the first-level wired NoC network 4-router. To enable single-hop communication between distant tiles that would otherwise require multiple-hops in the classical wired network, NoC tiles are equipped with radio hub transceivers. In a WiNoC, a reliable routing algorithm is necessary to prevent situations such as deadlock, livelock, and starvation in the network.

The routing algorithm plays a crucial role in the WiNoC architecture, as it determines the path taken by packets during transmission from the source to the destination [19]. The choice of routing algorithm used in the on-chip communication network is a key distinguishing factor among various proposed architectures. This section specifically focuses on the commonly used routing algorithm for the mesh topology. The mesh topology consists of P rows and Q columns [28], where the IP cores are connected to their respective routers, and the routers are interconnected by wires. Additionally, some other routers are connected to a radio hub, forming a subnet that is wirelessly linked together. The simulations used in this paper were based on four different routing algorithms, which are listed in Table 1 [29].

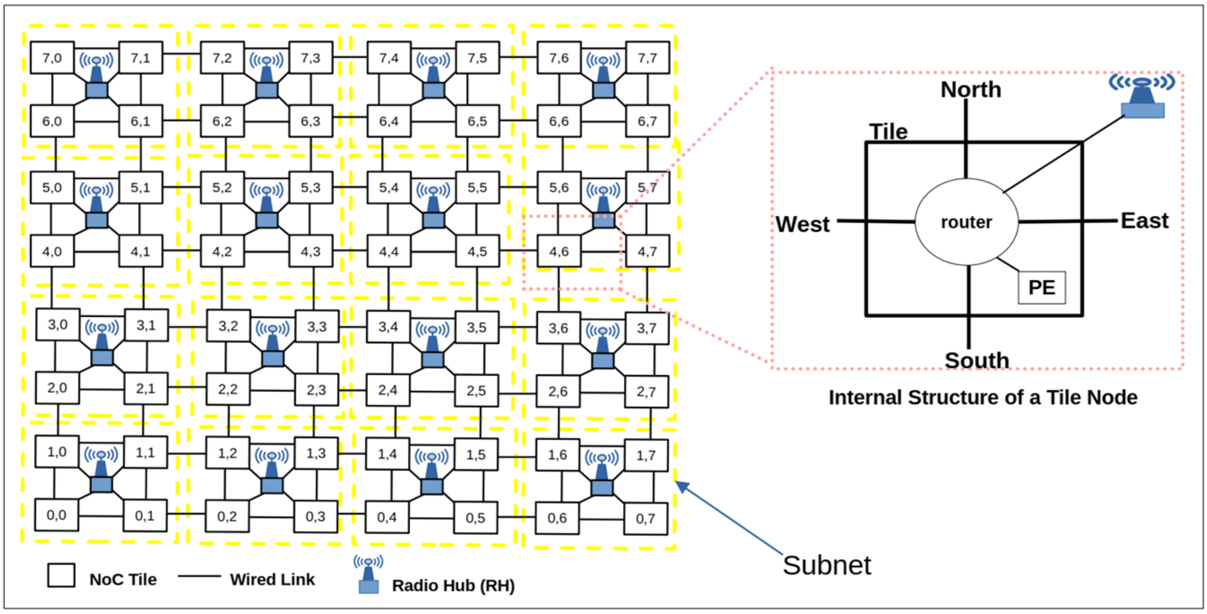

Figure 1. 8x8 WiNoC Architecture with 4x4 Radio-hubs and 16-Subnets

Table 1. Routing Algorithm

Basic Comparison	XY Routing	Odd-Even Routing	West-First Routing	DyAD Routing
Define	It is designed to improve the performance of packet routing and reduce congestion in large-scale systems.	It is an adaptive, distributed routing algorithm.	The algorithm is a type of partially adaptive routing algorithm.	The algorithm is a hybrid of deterministic and adaptive routing schemes, combining the benefits of both.
Usage	XY routing is known to be deadlock and livelock-free, meaning that it is designed to prevent both types of situations from occurring in network-on-chip communication.	Odd-even routing algorithm is capable of providing multiple routing paths and preventing deadlocks effectively.	It restricts packets to first go south or west, and then north or west, when making routing decisions to reach a destination node.	The DyAD algorithm is often described as an intelligent routing algorithm because it combines two routing techniques to provide more efficient routing.
Routing Decision	XY routing is to move packets in the X direction first and then in the Y direction.	In even columns, it permits turns while imposing restrictions on certain turns in odd columns.	The packets are sent first towards the west direction, and if it is not possible, they are then directed towards the south direction.	Deterministic routers are more appropriate for low packet injection rate, whereas adaptive routers are better suited for high packet injection rate situations to manage congestion and prevent network saturation.
Routing Techniques	Distributed deterministic routing techniques.	Distributed adaptive routing algorithm.	Partially adaptive routing techniques.	It uses a combination of deterministic and adaptive routing to efficiently route packets in the network while avoiding deadlocks.

4. Experimental Setup

This section describes the experimental setup used to evaluate the impact of routing algorithms, subnets, and virtual channels on the performance of NoC and WiNoC architectures in terms of Packet Injection Rate (PIR). The study employed a mesh-based topology for the on-chip communication network due to its natural layout, which can be easily mapped to an IC, and its scalability. Simulations were conducted using Noxim [30], a cycle-accurate System C simulator, with various traffic scenarios and different network scales, subnet sizes, and virtual channel numbers to investigate the behavior of each architecture under different conditions. The simulations included three network scales (8x8, 16x16, and 32x32), different subnet sizes (2, 4, 8, and 16) and virtual channel numbers (2, 4, and 8).

Moreover, we conducted experiments for various traffic distribution patterns, where we used 8x8, 16x16, and 32x32 network sizes with different numbers of subnets and virtual channels. The study also investigated the impact of radio hub allocation and placement in the WiNoC architecture concerning both small and large networks with respect to subnets and virtual channels. The simulation setup is summarized in Table 2, and the different traffic distributions used are briefly discussed in Table 3. The utilized tools effectively assessed the performance trade-offs between WiNoC and mesh NoC architectures, providing valuable insights into their respective efficiencies. This analysis considered parameters such as global average delay, network throughput, energy consumption, and average wireless utilization.

Table 2. Simulation Setup

Parameter	**Description**
Network Sizes	8x8, 16x16, 32x32
Number of Radio Hub	2x1, 2x2, 2x4, 4x4
Number of Channels	2, 4, 8
Simulation Time	100 000
Technology	65 nm
Clock Frequency	1 Ghz
Switching Mechanism	Wormhole
Radio Access Control	Token Packet
Selection Strategies	Random
Flit Size	32 bits
Routing Algorithm	XY, West-First, Odd-Even and DyAD
Traffic Patterns	Random, Butterfly, and Shuffle
Wireless Data Rate	16 Gbps
Wireless Communication	Millimeter-Wave

Table 3. Traffic Distribution

Pattern	**Description**
Random	The traffic is sent randomly from the source to the destination, and each node has an equal probability of sending packets to other nodes.
Shuffle	Bit-permutation traffic from source to destination with shifted order address.
Butterfly	Splitter networks routing time on certain permutations.

5. Results and Discussion

The experiments were conducted using network sizes of 8x8, 16x16, and 32x32. The number of subnets used in this research are; 2, 4, 8 and 16 along with three types of IP cores (64, 256 and 1024) in the network. The comparison between WiNoC and mesh NoC was done using the following metrics: network throughput, energy consumption, and average wireless utilization.

5.1. Impact of Virtual Channel on Network-on-Chip

The impact of virtual channels (VCs) on three different network sizes (64, 256, and 1024 nodes) was analyzed through simulations under various traffic distributions specified in Table 3.

5.1.1. Impact of Virtual Channel on Network Latency

Latency is a term used to describe the amount of time it takes for data to travel across a network, typically measured as the delay between sending a packet and receiving a response. It quantifies the time it takes for packets to reach their intended destination and return back to the sender. Network latency is an essential metric used to assess network performance and is determined by factors such as distance, efficiency, network congestion, and processing time. In this research, the interest is in the efficiency of the number of virtual channel (VC) effect on reducing the delay and improving the system performance. Figure 2 shows average network delay with an increase in VC from 2 to 8 under variation of PIR for each VC. The research showed that with an increase in VC for each architecture (64, 256 and 1024 nodes), the delay is still under control and the network runs well. Though in 1024 nodes saturation occurred at PIR = 0.005, for 256 nodes at PIR = 0.01 and for 64 nodes at PIR = 0.02.

5.1.2. Impact of Virtual Channel on Network Throughput

The impact of virtual channels on network throughput was investigated and presented in Figure 3. For every network, the IP and VC counts must match. Additionally, if the VC is larger than what the system requires, it will be in an inactive state and useless because it cannot transfer packets from the source to the destination node. The Network Throughput comparison of the various network sizes in Figure 3 illustrated that the bigger the network architecture, the better the network throughput.

5.1.3. Impact of Virtual Channel on Energy Consumption

The lower the energy consumed, the better the system efficiency. Figure 4 shows the energy comparisons of three architectures with three VC. The energy consumption in this research demonstrated that the design has an incremental trend as the networks increase in size. 32×32 architecture utilized more energy consumption than the other two architectures. Though 8-VC consumes more energy when compared with the other two VCs used, 4-VC is better regarding energy consumption.

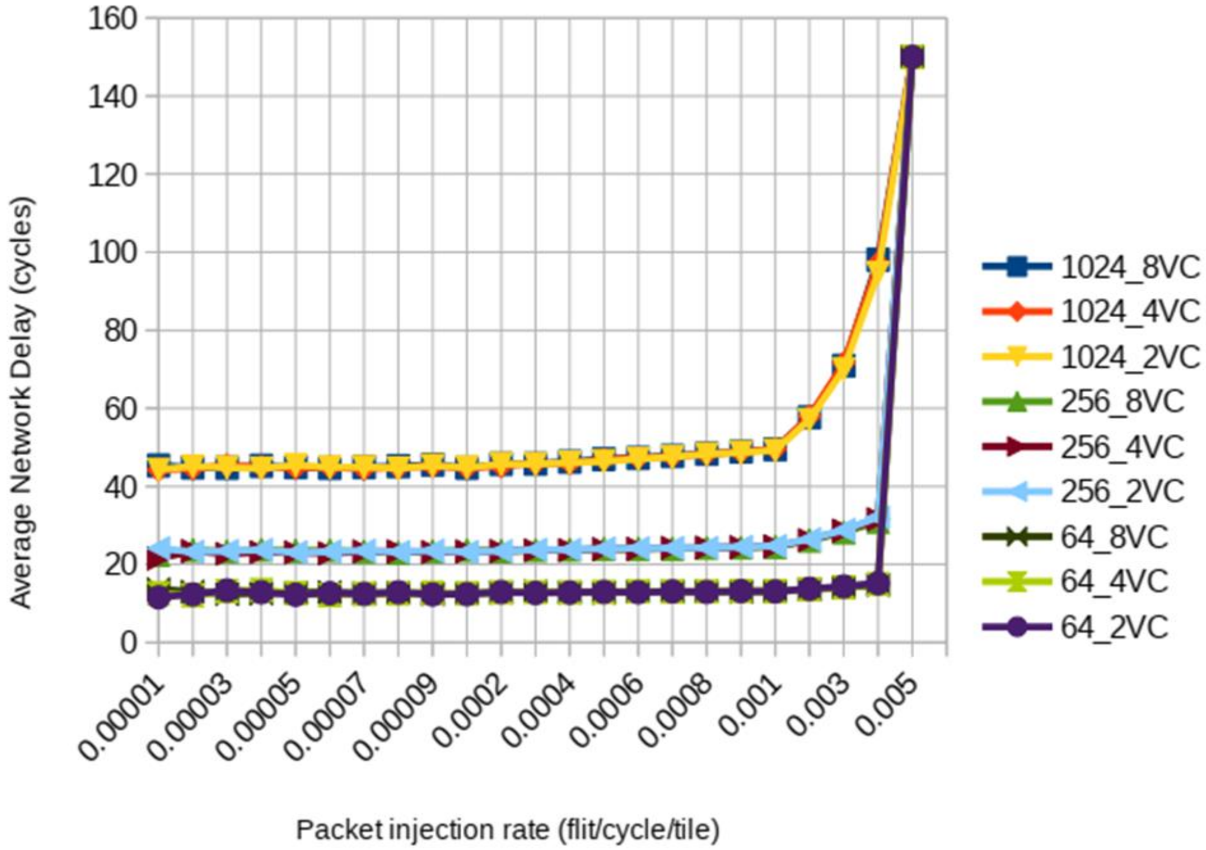

Figure 2. Average Network Delay in NoC

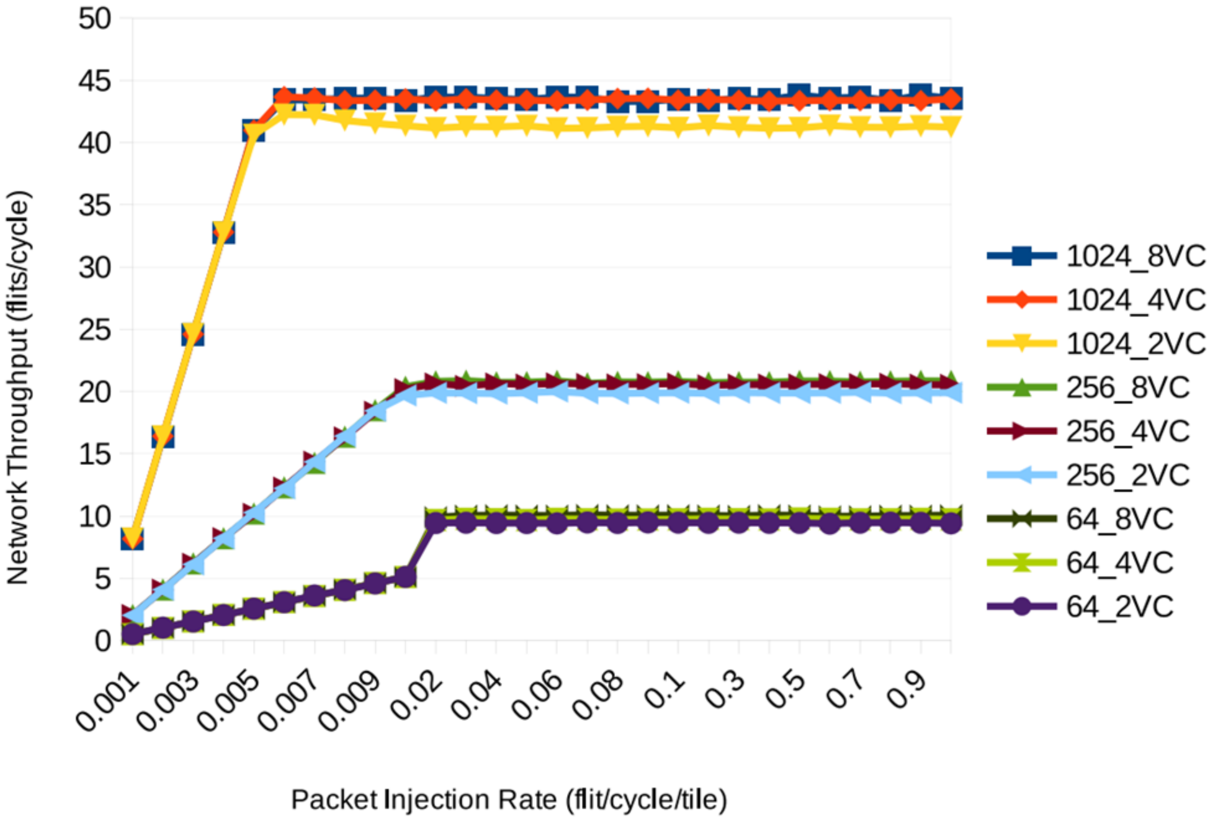

Figure 3. Network Throughput in NoC

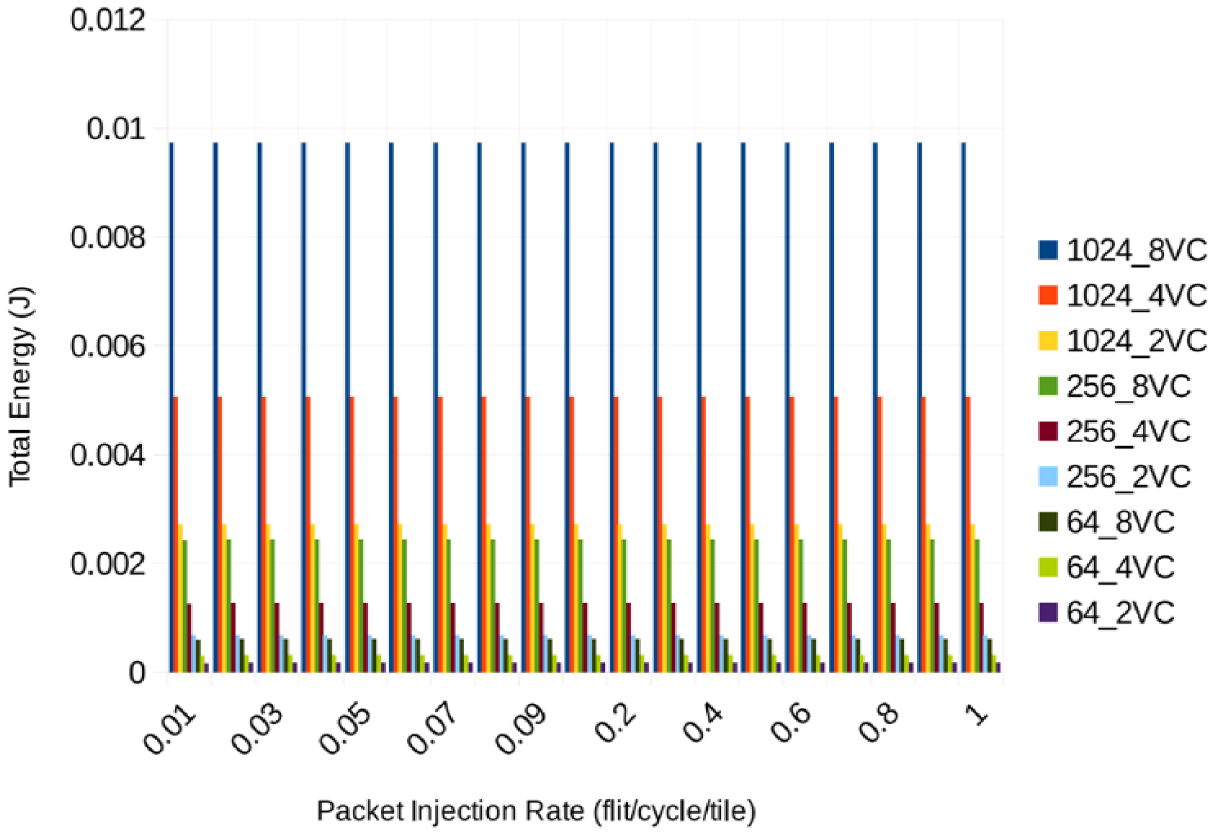

Figure 4. Energy Consumption in NoC

5.2. Impact of Virtual Channel and Subnet on WiNoC

This section examines how the network performance of different-sized IPs (64, 256, 1024) is affected by the use of Virtual Channels (VCs) and subnets, with varying numbers of subnets (2, 4, 8, 16) employed Subnets are logical partitions of a network into smaller segments, allowing for inter-subnet communication with shorter path lengths compared to a single NoC spanning the entire network system.

5.2.1. Impact of Virtual Channel and Subnet on Network Latency

In a network without subnets, communication between distant IPs requires more intermediate nodes, resulting in longer paths, compared to a network clustered into smaller groups of cores. When two or more cores internally transmit data in the same subnet rather than outside subnet communication, it transfers faster as the delay time is reduced. The study evaluated the impact of virtual channels (VCs) on both subnet and network architectures in WiNoC, where all tiles within a subnet were wirelessly connected to the subnet's hub, which in turn communicated with other subnets' hubs in the network. The delay cycle is constant for almost all the VCs with respect to each architecture size. The impact of VCs in WiNoC is minimal, but using subnets, notable improvements were observed as illustrated in Table 4.

Table 4. Saturation points in Network delay comparison in WiNoC & NoC

WiNoC: Global Average Delay (Cycle)			
2VC	**32x32**	**16x16**	**8x8**
2H	0.005	0.009	0.01
4H	0.005	0.009	0.01
8H	0.005	0.005	0.007
16H	0.002	0.002	0.002
4VC			
2H	0.005	0.01	0.01
4H	0.005	0.01	0.01
8H	0.005	0.004	0.007
16H	0.002	0.002	0.002
8VC			
2H	0.005	0.01	0.01
4H	0.005	0.01	0.01
8H	0.005	0.004	0.007
16H	0.002	0.002	0.002
NoC: Global Average Delay (Cycle)			
2VC	0.005	0.01	0.02
4VC	0.005	0.01	0.02
8VC	0.005	0.01	0.02

This result showed that 8×8 architecture is better than other architectures used WiNoC and it will be more useful for network latency design. Figure 5 shows the highest level of efficiency attained by each architecture. This is because operating the network at a higher PIR rate enables the nodes to utilize their maximum capacity. In Figure 5, we have the following; (a) Network delay with 2VCs, (b) Network delay with 4VCs and (c) Network delay with 8VCs.

5.2.2. Impact of Virtual Channel and Subnet on Network Throughput

Network throughput, which is determined by a network's capacity to handle the requested packet injection rate (PIR), serves as a fundamental metric for evaluating the efficiency of network performance. It provides insights into how effectively the network can process and manage data traffic. A high level of unsuccessful packet deliveries results in lower throughput, while effective network design leads to higher throughput. However, many factors can affect network throughput, including congestion and packet losses. Figure 6 compares the network throughput for three wireless network sizes (8×8, 16×16, and 32×32) in terms of VC and subnets. The network throughput decreases as the number of subnets increases relative to the size of the network architecture, and the impact of VCs on network throughput is minimal since all three VCs produce comparable results for all.

5.2.3. Impact of Virtual Channel and Subnet on Energy Consumption

The energy consumption comparisons of VC and subnets regarding the three different architectures in XY algorithm are shown in Figure 7. The results show that the energy consumption increases as the network size grows, the bigger the network architecture in respect to each subnet used, the more energy consumption for each case. In overall, the 8×8 architecture used lower energy in each subnet than other architecture used.

5.2.4. Impact of Virtual Channel and Subnet on Wireless Utilization

The utilization of the wireless medium in a network improves the efficiency of communication through radio hubs. The term "wireless utilization" refers to the ratio of connections that use, either completely or partially, the wireless medium to the total number of communications in the network. Figure 8 show wireless utilization with respect subnets and VCs of XY-algorithm. As the number of subnets increases in the network architecture, there is a noticeable rise in the utilization of wireless resources. Among the different network architectures evaluated, the 8x8 architecture exhibits the highest proportion of wireless usage. This is attributed to the fact that this architecture has a dense distribution of radio hubs within it.

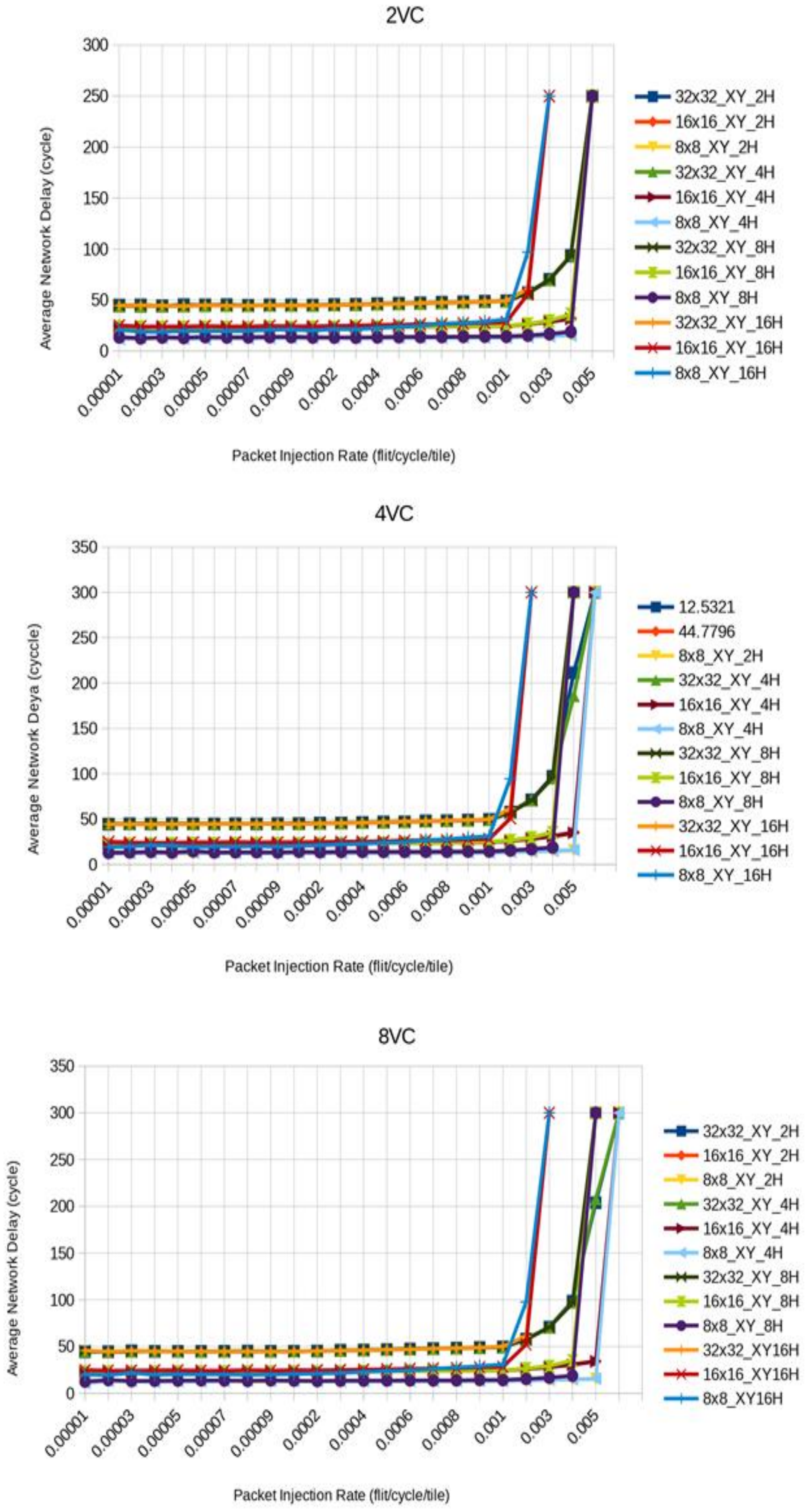

Figure 5. Average Network Delay of 3-WiNoC Architecture with varying PIR

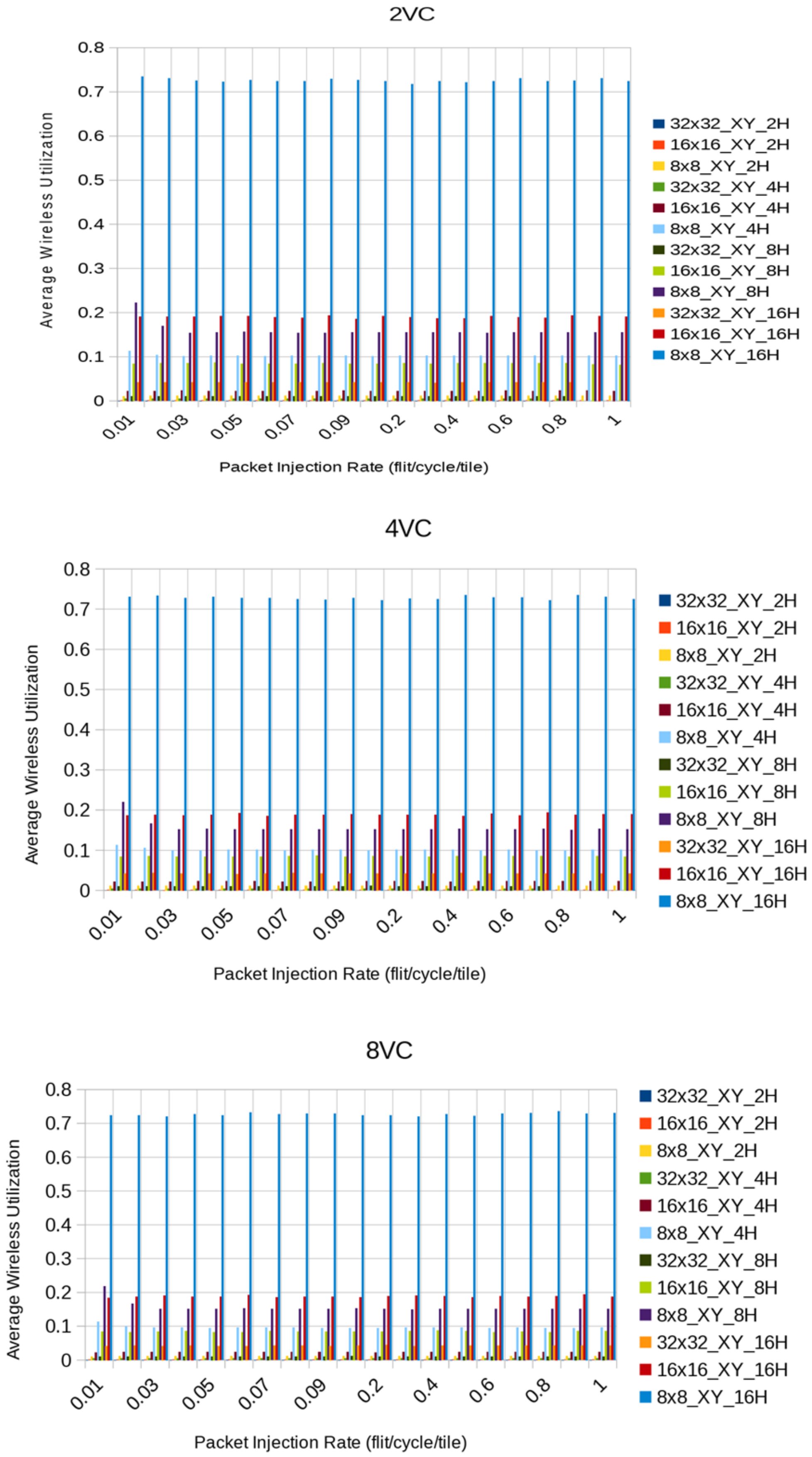

Figure 6. Network Throughput of 3-WiNoC Architecture with varying PIR

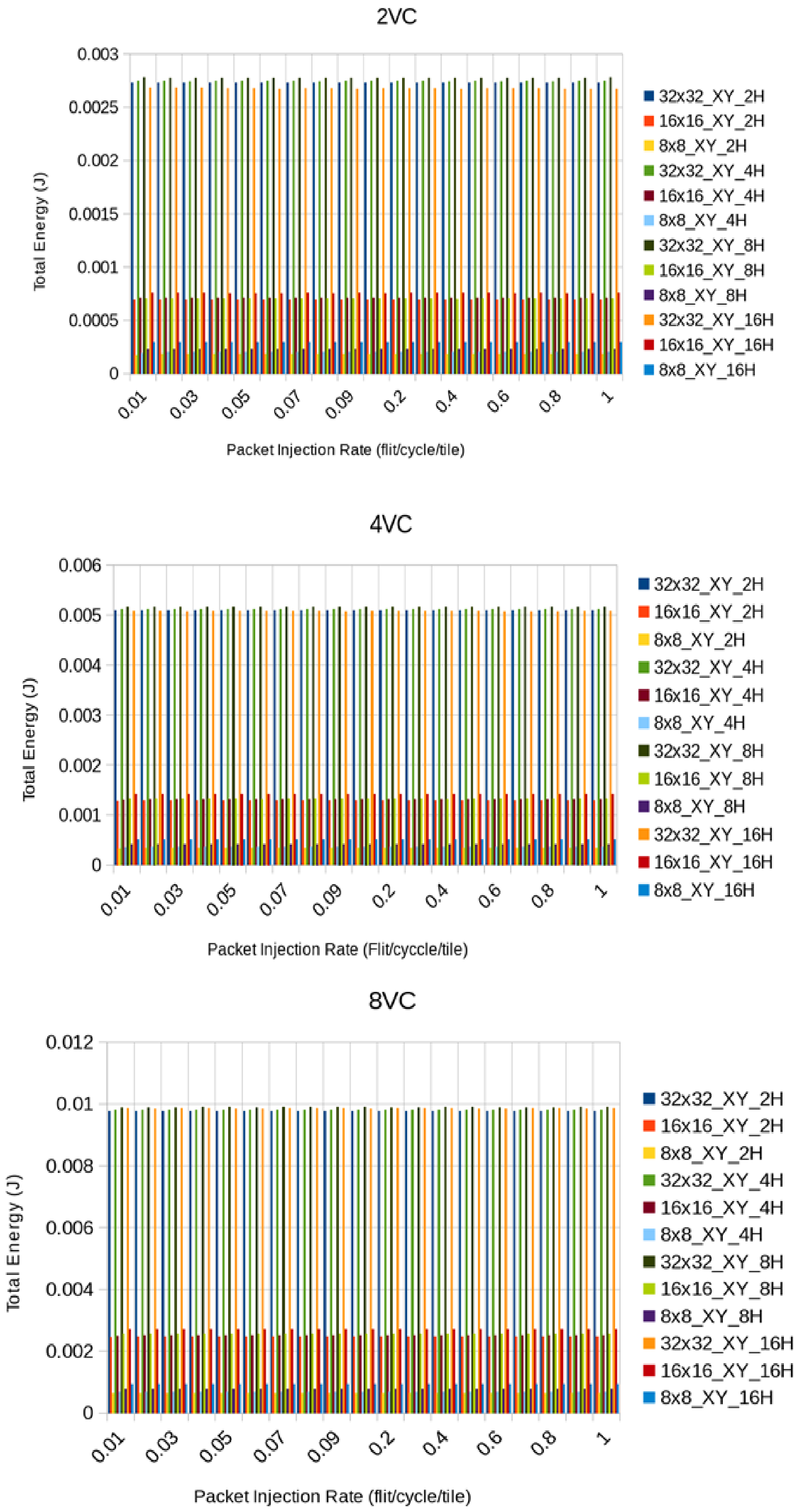

Figure 7. Energy Consumption of 3-WiNoC Architecture with varying PIR

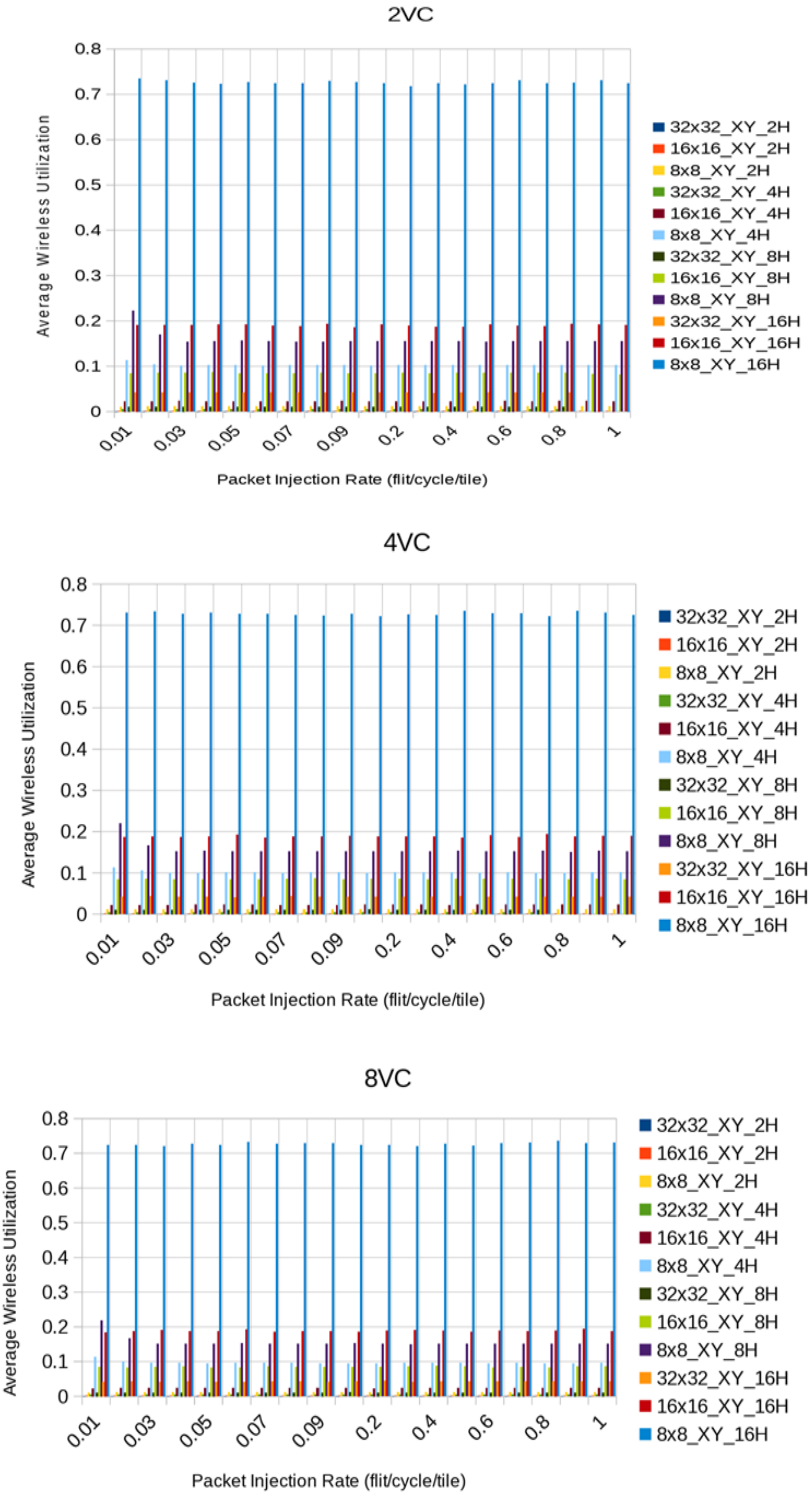

Figure 8. Wireless Utilization of 3-WiNoC Architecture with varying PIR

Finally, the results of the experiments indicate that virtual channels (VCs) do not significantly affect average network throughput and network delay in a NoC, but do have a considerable impact on energy consumption. As the number of VCs increases relative to the network size, the energy consumption also increases. In WiNoC, subnets improve performance efficiency, but VCs have little effect. Therefore, careful consideration should be given to the number of VCs used in a NoC, while subnets can be used to improve the performance of a WiNoC.

6. Conclusions

The study examined the impact of subnets, virtual channels, and routing algorithms on network performance in classical mesh NoC and WiNoC architectures for varying network sizes. The findings revealed that the 8x8 architecture in the 64-node WiNoC had the highest wireless utilization and energy efficiency, which can be attributed to the dense distribution of 16 radio hubs. However, exceeding the authorized range of subnets led to a decrease in throughput at lower PIR, necessitating designers to prioritize either fast data transfer or high throughput performance. Furthermore, the impact of virtual channels (VCs) on average network delay was found to be minimal in WiNoC and negligible in NoC. On the other hand, subnets considerably improved the performance efficiency of WiNoC's architecture. To further advance the research in this area, future studies could investigate the impact of subnets on various WiNoC architectures, including McWiNoC, WCube, and iWise.

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