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Journal for Control, Measurement, Electronics, Computing and Communications

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/taut20

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AUTOMATIKA
2023, VOL. 64, NO. 4, 689–702
https://doi.org/10.1080/00051144.2023.2213927

RESEARCH ARTICLE

Proactive flow control using adaptive beam forming for smart intra-layer data communication in wireless network on chip

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ABSTRACT

Systems-on-chips need numerous predesigned cores to advance. NoC enables Multi-Core SoCs (MC_SoCs). Conventional NoC cores use power and latency on multi-hop wired connections. An effective Wireless Network-on-Chip (WiNoC) architecture can overcome NoC difficulties. On-chip antennas, transceivers, and routers replace multi-hop cable connections with high-bandwidth single-hop wireless networks using WiNoC. Nanotechnology development demands fast data transfer to overcome performance bottlenecks from sharing memory modules and connecting fabrics. This research offers a new Proactive Flow control using Adaptive Beam formation for Smart Intra-layer Data Communication technique(PF_SDC) to optimally use network resources and assure QoS in Wireless Network-on-Chip for next-generation nano-domain technology. Hybrid NoC architecture optimises application admission for data transfer over wired and wireless interconnects. Data traffic is managed by a fuzzy inference-based Intelligent Head Agent (IHA). Queue load predicts router status for the fittest path selection. IHA initiates beams at angles to admit data flow towards the target while utilising the least amount of network power and resources. A simulation model shows that the proposed system may be applied in real-world applications and consumes little power with good throughput.

ARTICLE HISTORY
Received 13 February 2023
Accepted 9 May 2023

KEYWORDS
Wireless network-on-chip; adaptive beam forming; intelligent head agent; fuzzy inference; intra-layer communication

1. Introduction

Advances in digital evolution necessitate applications ranging from automobiles to avionics to meet people's different needs. Because of the dynamic nature of programmes running on minicomputers and smartphones, more transistors must be added to microchips to make them more powerful. Network-on-chips (NoCs) [1] serve as a communication backbone in multi-core systems-on-chip (SoCs) [2], allowing for a high level of integration. Traditional scaling, for example, cannot fulfil the performance needs of NoC infrastructures. Furthermore, future technology upgrades and the desire for low-power, high-speed interconnects necessitate going beyond traditional interconnect architectures. Wireless NoCs (WiNoCs) [3], an on-chip wireless communication network using miniaturized on-chip antennas, is envisioned as a breakthrough technology capable of offering considerable performance gains for multi-core SoCs. As a result, interconnect methods such as multi-band RF transmission line interconnects (RFI) [4], on-chip photonic interconnect [5] and wireless interconnects [6] have been investigated. The compatibility of the underlying technology of small metallic antennas and transceivers [7] with CMOS manufacturing techniques has made wireless connectivity functioning in the millimetre wave (mm-wave) band a near-term solution among these choices. Multiple wireless transceivers sharing the same wireless channel improve energy efficiency and performance in mm-wave wireless NoC [8, 9] systems. To fully harness the benefits of wireless communications, architectural improvements are required. By reducing power consumption, wireless interconnects can enable high bandwidth and low latency communications over long distances. Wireless implementations also reduce the amount of space taken up by wires. In general, radio frequency (RF) transmission will enable broadcast and multicast communications. On-chip communication over short distances (millimetre range) requires less transmission power than traditional, long-range wireless communications (metre range), making it a viable solution for global interconnects. Wireless interconnects have several advantages, including: (i) low power transmission from edge to edge across the chip, (ii) no wires and (iii) cost effectiveness due to CMOS compatibility.

The technique "Proactive Flow control utilizing Adaptive Beam forming for Smart Intra-layer Data Communication (PF SDC)" is proposed in this paper to maximize overall network performance without unnecessary overhead. It combines mm-wave connection technology in WiNoC with design considerations

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to create a simple, light-weight and fair medium access control (MAC) incorporating appropriate on-chip antennas, wireless routers and transceivers to provide efficient flow control in wireless links. In a Multi-Core Wireless Network-on-Chip (WiNoC) System, the suggested PF SDC model utilizes innovative ways to efficiently utilize network resources to achieve guaranteed Quality of Service. To enhance applications' access utility for efficient data communication, the modal uses a hybrid NoC design [10] that uses both wired and wireless interconnects. The entire system is divided into clusters, with an IHA serving as the head node for intra-layer communication in each cluster. The IHA includes a Proactive Flow Control with Adaptive Beam Formation (PF ABF) module that takes advantage of the Admission Control with Fuzzy Inference (ACFI) mechanism for angular data exchange. The primary goal of IHA is to estimate and predict the router's current state. This estimation self-organizes the nodes to decide whether the data flow session can be admitted or rejected along the fittest path, making the entire network intelligent for instantaneous decision making and ensuring that the system uses the least amount of power and resources possible during network communication. Our proposed methodology was created using a MATLAB SIMULINK prototype. The performance of PF SDC is compared to existing techniques such as 2D Mesh, RFI, inter WISE, and SW WiNoc. The results revealed that the ACFI engine in the PF SDC model optimizes the admission control working procedure to achieve good throughput with low power by selecting and admitting service via the dependable path for efficient transmission. The remainder of the paper is laid out as follows. In Section 2, we talk about related work. In Section 3, we talk about our proposed PF SDC system framework. In Section 4, we show simulation results and analysis, and in Section 5, we talk about where to go next.

2. Related work

This section describes various recent research projects that primarily employ wired and wireless mesh-based NoC architectures with on-chip wireless connectivity. In [11], the author suggests a WCube, a hybrid system that uses both wired and wireless channels for communication among nodes, with a centralized wireless hub in each group. There are 64 nodes in the group, each with a fixed wire for intra-group communication and a wireless link for inter-group communication. The wireless hub uses a frequency range of 100–500 GHz and consumes about 4.5 pJ/bit. The modal improves latency with power consumption similar to that of a mesh network. Ganguly et al. [12] developed a hybrid solution that uses many centralized wireless hubs connected in a ring arrangement. With the use of on-chip optical modulators and carbon nanotube antennas, the approach achieves a low energy of 0.33 pJ/bit. On CMOS ultra wide band technology, [13] considers a 2D mesh-based design with a 4×4 multi-core NoC. To connect to the network, the model employs RF nodes. Single or many hops are used to deliver packets from source to destination. The modal employs location-based routing with time-hopping multiple accesses to increase NoC's performance. This mode improves execution time by 23% and reduces end-to-end latency by an average of 65% when compared to an 8×8 (64) cores-based wire-line mesh NoC architecture. In [14], the author suggests a hybrid technique for propagating RF signals at light speed using electrical lines and an RF transmission line. The use of a low-energy RF transmission line of 1.2 pJ/bit improves the performance of this approach. Due to its wireline technique for putting transmission lines on the chip, this method adds a small amount of area overhead. [15] proposes an inter-router wireless scalable express (iWISE) channel for NoC architectures in the mm-wave frequency range. The goal is to boost performance by lowering overhead and power consumption. The cores are laid out in a grid arrangement, with routers scattered across the network. In iWISE, each set has four clusters, each with four cores. For a 256-core system, this model provides a 2.5X performance boost while saving 2X power. The author of [16] uses miniaturized on-chip antennas as an enabling technology to demonstrate small world wireless NoC's (SW-WiNoC). The system is partitioned into numerous tiny clusters as part of the architecture. Each cluster functions as a smaller network with a smaller number of cores. The technology uses on-chip wireless communication to do intra-subnet communication rather than a single core-to-core communication that spans the whole system. The model's performance is tested with different types of traffic, and it is found that it outperforms the wired version by orders of magnitude in network throughput and latency by improving the way energy is lost.

Many research papers on hierarchical small-world wireless NoC architectures incorporating mm-wave wireless networks were investigated [17]. Only the mm-wave WiNoC has an acceptable flow control mechanism among all WiNoC architectures. However, finding an architecture that minimizes hardware costs while optimizing performance, accuracy and parameterization to assure the full benefits of interconnect technology is the key problem in on-chip WiNoc [18]. As a result, creating a simple yet effective medium access control system that adjusts to changing traffic demands for applications running in multi-core systems is critical [19]. This study proposes a basic light-weight MAC accompanied by appropriate flow management techniques to enable maximum exploitation of the wireless medium for WiNoCs in order to maintain the projected WiNoC performance [20].

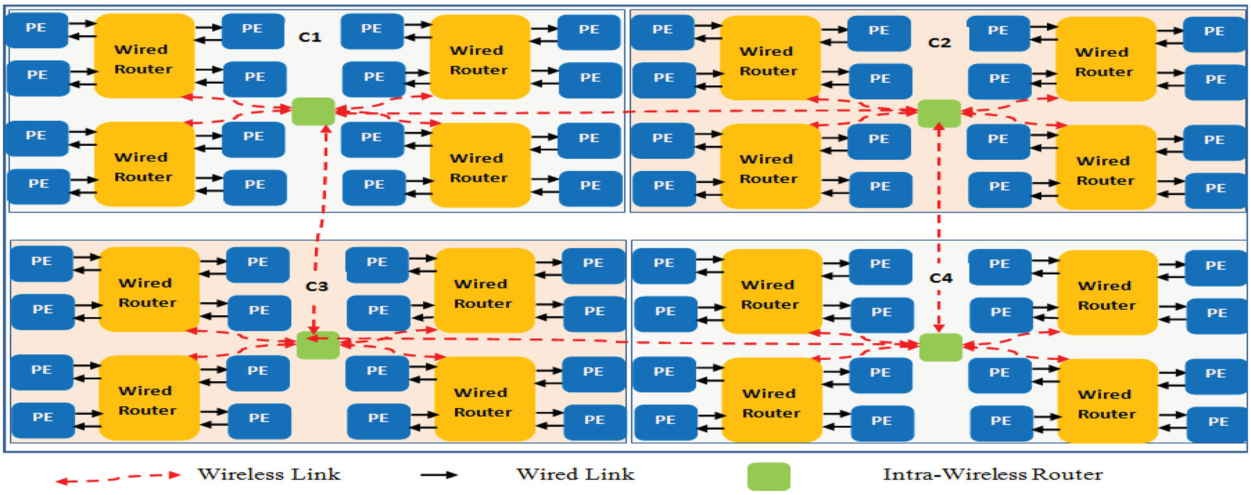

Figure 1. The PF_SDC multi-core topology model.

3. Proactive flow control using adaptive beam forming for smart intra-layer data communication (PF_SDC) system framework

As illustrated in Figure 1, the suggested architecture is based on an 8 × 8 multi-core (64 cores) WiNoC topology. Each layer has four clusters, each with 64 cores (8 × 8 cores). Unlike mesh topologies, which connect each core or processing element (PE) to a router, the proposed PF SDC system creates a scalable architecture by sharing a single wired router among four PEs (cores and memories). In a mesh topology, 16 cores have 16 wired routers. However, in the suggested architecture, each cluster of 16 cores (4 × 4 cores) has 4 wired routers, as shown in Figure 1. A wireless router is also installed in the heart of each cluster, making it wirelessly accessible to all four wired routers. The Intelligent Head Agent (IHA) in each cluster is the wireless router. To make the most of the wireless medium, the IHA employs appropriate flow control methods. The routing method incorporating a wireless link should be used if it minimizes the total path length compared to the wired path between a pair of source and destination hubs without WIs. This can cause a hotspot in the WIs as multiple messages try to use WiFi shortcuts at the same time, overloading the WIs and increasing latency. This challenge can be solved using a proactive flow control approach with distributed routing. The goal is to use as little power and resources as possible to do intra-layer communication over a wireless link with low latency and high throughput.

Nomenclature used in the proposed model is summarized in Table 1.

The packets are divided into flits, which are smaller pieces. The header flit is the initial flit of a packet, and it contains control information for packet delivery such as the source address, destination address, operation type, packet type, role, priority, and payload size. The path flit is the second flit of the packet, and it provides the path information along with the packet's sequential number in the current transaction between the source and destination. The body flit, also known as the payload, is the third flit of the packet and contains the actual data to be transferred to the destination. The packet format, as shown in Figure 2, is made up of nine fields, including the Source (Sc), which is the communication's initiator. The destination core address is indicated by the letter DC. The type of transaction (read, write, conditional write, broadcast, etc.) is indicated by the operation (Op). The type of information being exchanged (such as data, instructions, or signal types) is indicated by type. The source component's role (e.g. user, root, etc.) is indicated by the role. The priority of traffic is classified by priority. The packet payload, or the number of bytes in the payload, is indicated by size. Payload denotes the actual data information created by the source core, whereas Path denotes the packet's registered path. PF. SDC assigns a proportional weight to each data flow to suit service needs. This is accomplished by setting the priority field in the header file to 0 or 1. Normal or Low Priority (LP) data traffic is coded as 0, while emergency or High Priority (HP) data traffic is coded as 1. Emergency traffic

Table 1. Nomenclature of PF_SDC model.

Notation	Description
L_{id}	Layer identification number
SNx	x coordinate of the subnet
SNy	y coordinate of the subnet
PEflit	Processing element header flit
PE^{i}_{id}	Processing element identity
PE^{i}_{load}	Processing element load
PE_{TS}	Processing element time stamp
PE_{P_value}	Processing element priority value
WR_{id}	Wired router identity
WRL_{status}	Wired router load status
WRRAflit	Wired router ready to accept flit
WRBflit	Wired router busy flit
$TWRL_{status}$	Threshold wired router load
IHAflit	Intelligent Head Agent header flit
IHA_{id}	Intelligent Head Agent identity
IHA_{TS}	Intelligent Head Agent time stamp
$IHA^{i}_{node\_status}$	Intelligent Head Agent node status

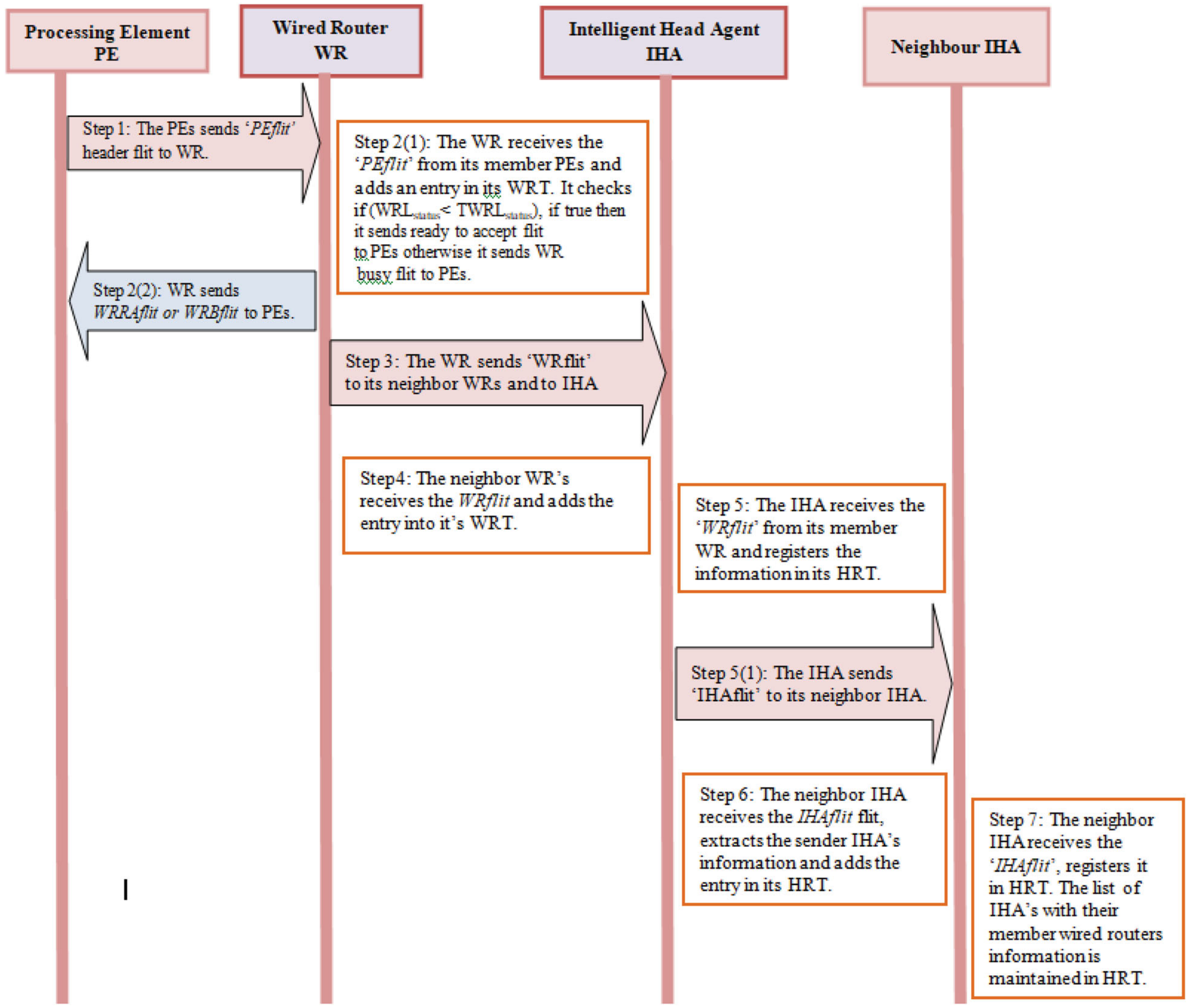

Figure 2. Fittest path selection using IHA.

needs superior service. As a result, priority in procuring network resources is usually given to emergency or real-time traffic for rapid and reliable transmission. The most extensively used packet scheduling algorithms are Weighted Fair Queuing (WFQ) [29], Weighted Round Robin (WRR) [30], and Strict Priority (SP) [28]. A tight scheduling discipline with a probabilistic priority (SPP) queuing mechanism is used in the suggested model to cope with the starving problem and make priority discipline adjustable. SPP distinguishes itself from conventional scheduling algorithms by being "simple to develop and configure, effectively utilizing existing bandwidth and requiring very little memory and processing power." SPP looks at how likely it is that a queue will be served and offers different levels of service based on traffic by giving each queue parameters (high or low priority).

3.1. Phase of PF_SDC model

The specifications and functionality of the various phases of the proposed model are detailed in this section. The suggested PF SDC model's functionality is divided into the following phases:

- Phase I: Cluster Organization for Fittest Path Selection using Intelligent Head Agent
- Phase II: Proactive Flow control using Adaptive Beam Formation for Intra-layer Communication
  - Antenna Orientation and Directivity Mechanism
  - Admission Control using Fuzzy Inference Process.

3.1.1. Cluster organization for fittest path selection using intelligent head agent

The suggested system is divided into groups by the proposed plan. The cores are grouped into clusters to maximize data transfer. Each layer is divided into four clusters in the proposed 8 × 8 WiNoC design. Each cluster has 16 cores, four wired routers, and one wireless router. Unlike other topologies, IP cores (also known as Processing Element – PE) are connected to wired routers via wired interconnects. Each cluster's wireless router is connected via wireless link to its member wired routers and neighbour wireless routers in neighbouring clusters. In PF SDC, the clustering approach adheres to constraints such as,

(1) A core in the network can be part of only one single cluster: $\forall_i : \sum_{(j=0)}^{3} P_{ij} = 1$ where P indicates whether a core belongs to a particular cluster or not. P contains either 0 or 1 as entries, where 0 signifies the absence of a core in a particular cluster and vice versa.
(2) Each cluster will have exactly 16 cores with 4 wired routers (WR).
(3) Each WR is connected to exactly 4 cores.
(4) Each cluster contains only one wireless router called Intelligent Head Agent (IHA).

Intelligent Head Agent: The wireless router in each cluster acts as a head node and is referred to as the Intelligent Head Agent (IHA) of the cluster. The proposed model consists of four IHA nodes in each layer. The primary objective of IHA (Wireless Router) is to perform intra-layer communication, i.e. the IHA employs communication via horizontal wireless links with its neighbour IHAs in the same layer. It comprises a mm Wave wireless transceiver and an on-chip zigzag Ansoft HFSS (High-Frequency Structural Simulator) antenna specifically characterized to initiate radiation in an angular pattern. The mm Wave transceiver's power of the wireless interconnect in IHA is optimized to cover the entire chip or the layer area. This enables intra-layer communication with neighbour IHAs in a single-hop fashion. The primary objective of IHA is to

- Exploit Admission Control using Fuzzy Inference (ACFI) for effective data communication via the Proactive Flow Control using Adaptive Beam Formation (PF_ABF) module.
- We significantly reduce congestion and interference caused in wireless channels through angular beam formation. The angular dispersion of information towards the target prevents data from being broadcast throughout the layer or the chip.
- Optimizes resource utilization by intelligently explo ring neighbour's node status using metrics such as load, link quality, and service provided.
- Manages transmission by adaptively directing packets towards their destination by-passing potentially congested areas.

Fittest Path Selection using IHA: The goal of IHA is to use flow control mechanisms to optimize traffic regulation and to permit data traffic via dependable links rather than weak or declining links. The steps in the procedure are as follows:

Step 1: Regularly, the member PE's sends PEflit (PE^{i}_{id}, PE^{i}_{load}, PE_{TS}, PE_{P_value}), a dedicated probe signal (header flit) to the Wired Routers announcing its queue load information.

Step 2: Upon receiving the "PE_{flit}" from its member PEs, the WR extracts the information from "PEflit" and adds an entry to its routing table called Wired Routing Table (WRT). The WR maintains a buffer load value (WRL_{status}) which indicates its current load status. The value of WRL_{status} is either 0 (the buffer load of WR is low and is capable of processing more data) or 1 (the buffer load of WR is above optimal or high and is currently may not be able to process data from PEs). Significantly, the WR validates its current load status (WRL_{status}) with the threshold router load status ($TWRL_{status}$ – a static value maintained by WR across the network). Only when it's current load status is less than the threshold load status ($WRL_{status} < TWRL_{status}$), it sends $WRRA_{flit}$ (ready to accept) notification to its member PEs (priority of notification is given to high priority PE's with $PE_{P\_value} = 1$) otherwise, it sends WRBflit (busy state) notification indicating it's busy state. Upon receiving the $WRRA_{flit}$, the PEs initiates transmission to WR. Similarly, upon receiving the WRB_{flit}, the PEs stop transmission to WR and wait until it receives the $WRRA_{flit}$ to proceed further transmission. This notification ensures member PEs to prevent unnecessary transmission to WR when its load is high and busy.

Step 3: The Wired Router in each cluster keeps broadcasting $WR_{flit} = [WR_{id}, WRL_{status}, ((PE^{i}_{id}, PE^{i}_{load}, PE_{TS}, PE_{P\_value}), \ldots)]$, the header flit to its neighbour WRs (connected through wired medium) and to the IHA (connected through wireless link). The $WR_{flittransmits}$ the entries of those PEs whose load is below the threshold PE load value (TPE_{load}) and whose priority is high. This information helps neighbour WR and the IHAs to select the most appropriate PEs for data transmission during path selection.

Step 4: The neighbour WRs receive the WRflit and adds the entry into its WRT. Therefore, the WRT of each WR contains it's as well as its neighbour WRs PE information. Similarly, neighbouring WRs share their PE and load status information with one another, which is then added to and kept in their respective WRTs.

Step 5: In addition, the IHA in each cluster also receives the "WRflit" from all its member WR. Upon receiving the flit, it registers its members (wired routers) information in its Header Routing Table (HRT). The IHA sends $IHAflit = [IHA_{id}, IHA_{TS}, MWR^{i}_{id}, MPE^{i}_{id}, IHA^{i}_{node\_status}]$, header flit to its IHA neighbours.

Step 6: When the neighbour IHA receives the IHAflit flit, it extracts the information from the sender IHA and adds it to its Header Routing Table (HRT). Each IHA has an HRT table that provides a list of neighbouring IHAs as well as their corresponding member wired routers and node status information. In a similar fashion, using the "IHAflit" transmission, all IHAs share their node status and member information with one another, which is then added to and kept in each of their individual HRTs.

Step 7: At regular intervals, the member PEs, WRs, and IHAs broadcast their header flit (PEflit, WRflit and IHAflit) to their network neighbours to register their current load and status information in their respective routing tables (Wired Routing Table and Header Routing Table). Each node can now select its reliable neighbour nodes based on the information in the routing table. This ensures that each node sends service queries exclusively to reliable neighbours (RNs), who then pass the queries to their RNs.

Step 8: A source core (S_c) transmits a "pflit" path flit to the wired router whenever it has data to relay to a destination core (D_C). If a reliable route to the destination core does not exist after receiving the "pflit", the fittest path between S_c and D_c is discovered by utilizing the following case scenarios:

Case 1: Source core and destination core exists in same cluster.

Upon receiving the "pflit", the source WR looks-up it's WRT to check if (PE_{id}) of Dc exists. If so, it indicates the destination core resides in same cluster, therefore the WR of destination core is retrieved. Using the information in location table, (table in which the location information of related to each nodes are maintained), the location of Dc is fetched and updated in "pflit" appropriately. The pflit is the sent to the source WR which uses the information in pflit to reach Dc via the fittest path. The Source Sc then triggers the data transmission to Dc along the path established.

Case 2: Source core and destination core exists in different cluster.

Upon receiving the "pflit" from the source core, the source WR looks-up it's WRT to check if Dc resides in the same cluster. If not, it sends the "pflit" to its IHA via wireless link. Upon receiving the "pflit", the source IHA looks-up in its HRT to find the neighbour IHA whose node_status is low ($IHA_{node\_status} = 0$), i.e. IHA which is strongly connected. If there are IHAs that satisfy the criteria, it further verify if Dc exists in them. If so, then the source IHA updates the "pflit" with its information and directly sends the path flit request to the strongly connected destination IHA. The destination IHA upon receiving the "pflit" looks into the HRT to fetch the WR information in which the destination core resides. The path information is updated in "pflit" during its traversal and finally is sent back to source WR. The Source Sc then triggers the data transmission to Dc along the fittest path discovered.

3.1.2. Proactive data flow control using adaptive beam formation (PF_ABF) for intra-layer communication

In the proposed PF_SDC model, the Intelligent Head Agent (IHA) plays a vital role in employing dataflow control using adaptive beam-formation for intra-layer communication. The IHA mm-Wave wireless transceiver with PF_ABF module for intra-layer communication is depicted in Figure 3.

It consists of an mm-Wave wireless transceiver and an on-chip zigzag Ansoft HFSS (High-Frequency Structural Simulator) antenna with an angular pattern of radiation. The silicon-integrated antenna is designed to work in the millimetre-wave (mm-wave) frequency range of a few tens to one hundred gigahertz. The mm-Wave transceiver's power is tuned to cover the full layer area, allowing single-hop intra-layer communication with neighbouring IHA's. The IHA includes the "PF ABF" module, which uses Adaptive Beam formation to utilize proactive flow control by commencing data flow in an angular fashion. The procedure involves the following steps:

(1) Mechanism of Antenna Orientation and Directivity
(2) Proactive Data Flow Using Adaptive Beam Formation

Antenna Orientation and Directivity Mechanism: The transceiver is responsible for a large portion of the energy used for communication. As a result, by orienting antennas properly, the transmission power of wireless communication can be lowered. The on-chip zigzag mm-Wave wireless transceiver The Ansoft HFSS antenna correctly determines the orientation and uses a radiation pattern in the required direction. The zigzag antenna has an axial length of 680 m and is made up of two generic antennas $R = 10$ mm and a silicon substrate with a wavelength of approximately 5.02 mm (in the millimetre wave range) calculated using the Friis equation [23]. The antenna uses a phase shifter and a controller to tune and radiate a beam in the appropriate direction. Following the path defined by "Fittest path selection" between the S_c and the D_C, further payload or body flits will follow that path, i.e. the source allows data traffic to go to the destination via the chosen path. If the destination does not exist in the same cluster as the source, data is sent to the source IHA. The IHA constructs a directed channel based on the intermediate IHA's position information. When IHA receives packets from its member routers, each millimetre wave transceiver (TRx) in IHA is enhanced to do the following:

Step 1: The IHA gets body flits from the WR of its members and figures out where the destination IHA is.
Step 2: Using the location data, the controller determines the desired beam creation direction.
Step 3: The phase shifter receives the direction from the controller and adjusts the angle to set the phase in the desired direction. The mm-Wave Transceiver changes the information into a beam and sends it in the right direction.

The suggested model consists of four IHAs, or four antennas on a die plane. By altering the transmitting

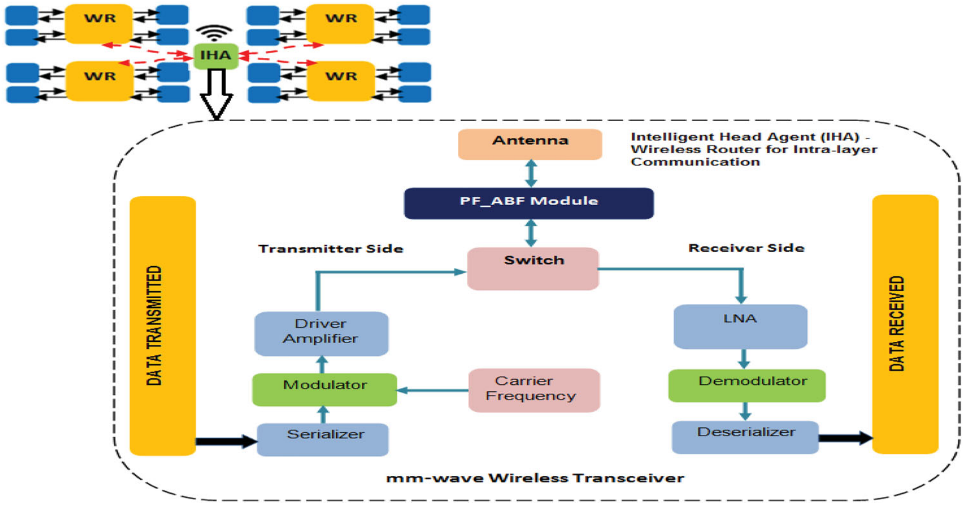

Figure 3. IHA mm-wave wireless transceiver with PF_ABF module.

antenna's orientation towards the receiver, the respective antenna directivity is optimized. The energy efficiency of a transmitter or receiver pair is improved by altering the directivity of the antennae in the desired direction. The suggested technique has a tiny overhead because each antenna requires a very simple phase shifter. It sets the directivity of the antennae orientation towards the receiver prior to data transmission to guarantee that the overall energy and power consumed are lower. When the antenna bandwidth is reduced, the power transfer in one direction is boosted, resulting in increased power gain. This method also blocks signals with the same frequency coming from different directions, while pointing the primary beam in the direction of the desired signal.

Proactive Data Flow using Adaptive Beam Formation: For efficient administration and distribution of shared resources, the IHA includes a PF_ABF (Proactive Data Flow utilizing Adaptive Beam Formation) module. It regulates the manner in which packets are forwarded in the network and in which direction they are forwarded. Packets may be misrouted or buffered due to a lack of resources. Due to limited buffers and link bandwidth, one or more packets may be diverted to an unfavourable link, stopped due to contention, or simply discarded when two or more packets seek to use the same network resource (e.g. a link or a buffer) at the same time. In IHA, proactive data flow refers to the degree of commitment to packet delivery.

The ACFI method is used by the model to efficiently handle incoming traffic and maintain optimal resource usage. The Admission Control with Fuzzy Inference (ACFI) procedure determines resource availability by calculating the node status ($IHA_{nodestatus}$) based on the queue load and packet type of each node. Figure 4 depicts the ACFI structure utilized in PF ABF (a). The ACFI procedure identifies the amount of resources used for high and low priority packets

Table 2. Crisp output node_status derived using QoS parameter.

	QLoad %		
P_{Type}	QL_{HP}	QL_{LP}	node_status
HP	H	H	H
	L	L	L
LP	H	L	L
	H	H	H

by estimating the present data traffic handled and the actual buffer available for accommodating other data services. Its main goal is to generate the "*node status*" – IHA_{node_status}, which determines whether the node is capable of providing the services that other nodes in the network have requested. Under varying network conditions, fuzzy logic (FL) [24] provides improved adaptability.

Fuzzy Linguistic variables are created by fuzzification of input variables such as (i) kind of data service – packet type (P_{Type}), and (ii) fluctuating queue load (QL_{HP} or QL_{LP}). The AND (&&) operator is used to create a fuzzy rule foundation by logically combining input variables. The following is an example of a fuzzy rule base:

If (P_{Type} = HP) && (QL_{HP} = H) && (QL_{LP} = H) then node_status = H

If (P_{Type} = LP) && (QL_{HP} = H) && (QL_{LP} = L) then node_status = L

The rule base is used by the Inference engine to construct the de-fuzzified value node status, which typically reflects the dynamic behaviour of traffic in node's buffers as well as the current node's available capacity. The node status generated from the Packet type and Queue load parameters is shown in Table 2.

The value 1 is assigned to node status with H, and 0 is allocated to node_status with L. At any given time, the node status value specifies whether a data flow session

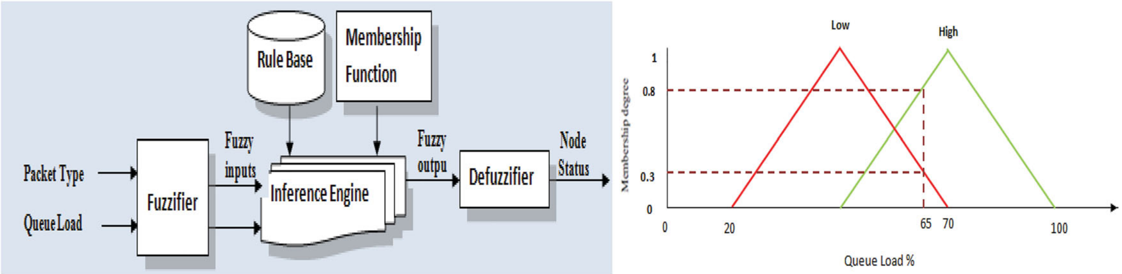

Figure 4. (a) Structure of ACFI process used in PF_ABF. (b) Triangular membership representation for queue load.

can be accepted or rejected. Figure 4 shows the triangle membership function for the queue load parameter, which represents the range of membership degree (b). Let's say the LP threshold is 75 percent and the HP level is 70 percent. The queue load percent will then be assigned a membership value in each set between 0 and 1 by mapping the current queue load onto the graph of the membership function. If the current QL percent is 65, for example, the degree of membership is between 0.3 and 0.8. As illustrated in Figure 4, the value can be fuzzified into LP with a degree of 0.3 and HP with a degree of 0.8. (b). The node status is one of the major factors considered by the proposed model when making decisions during data flow control. Each node's IHA_{node_status} serves as a direct link for determining resource availability. It guarantees that transmitting and receiving packets are coordinated to ensure that packets are delivered correctly and on time. Because the positions of the controller (IHA node) and the destination (core) are known and static, the beam formation enforced by the controller in the proposed model steers the beam as close to the target as possible. The controller provides non-overlapping spatial channels by reconfiguring the beams every R cycle, based on previous communication requests. The phase shifters are controlled by a beam table kept by the controller. The beam table stores information about the beam direction and phase shift vector pairs. The beam direction is calculated by comparing the direction with the position of the destination core. Because the number of beam directions is small, the IHA keeps a tiny beam table, making phase shifters straightforward. The beam radiated in the direction of the destination core is depicted in Figure 5. Beam forming minimizes the strength received in interference signal directions, resulting in nulls in the radiation pattern. It can electronically and digitally change and direct the radiation pattern of an antenna array, as well as adapt it to the environment, to improve performance and efficiency.

The power required for transmission throughout the data flow process is determined by numerous factors, including modulation type, transceiver noise, and attenuation introduced by the wireless medium. Given a transmitting and receiving antenna, the signal strength requirement is determined to determine the minimum transmitting power that assures a specified data rate and bit error rate (BER). The most extensively used modulation strategy in WiNoC for adjusting the baseband signal to the wireless medium is Amplitude Shift Keying (ASK) or On–Off Keying (OOK). The BER in ASK-OOK modulation is computed using,

$$BER = P(\sqrt{E_{bit}}/\sqrt{T_N}) \tag{1}$$

where E_{bit} denotes energy consumed per bit, T_{N} is the noise introduced by the transceiver and P denotes the standard normal distribution's tail probability.

$$E_{bit} = P_r/R_b \tag{2}$$

The power received by the receiving antenna is P_r, while the sending power required for a particular data rate. To calculate the minimal transmitting power required to reach the receiving antenna is given by

$$R_b.\,P_t = P_r/G_a \tag{3}$$

The attenuation introduced by the wireless medium (G_a 1) is represented by G_a.

Let P_t be the transmitting antenna's output power, and (t, t) denote the receiving antenna's relative angle. Similarly, place a receiving antenna at distance R with a relative angle (r, r) to the sending antenna. The receiving antenna's transmitting power, P_r, is calculated using Friis' transmission equation [23]. The Friis transmission equation, which is valid for $R > 2D2/$, can be used to calculate the fraction of transmitting power that reaches the receiving antenna's terminal, P_r, where D is the antenna's greatest dimension (axial length in this example) and is the wavelength 1.

$$\begin{aligned} G_a &= P_r/\,P_t \\ &= e_t e_r[(\lambda^2 D_t(\theta_t,\varphi_t)\, D_r(\theta_r,\varphi_r))\,/\,(4\pi R)^2] \\ G_a &= P_r\,/\,P_t \\ &= P_t e_r[(2Dt\ (t,t)\ Dr\ (r,r)) \end{aligned}$$

where e_t and e_r are the efficiencies of the transmitting and receiving antenna, respectively. The directivities of the transmitting and receiving antenna are D_t and D_r, respectively. λ is the effective wavelength. Antenna orientation and directivity play an important role in

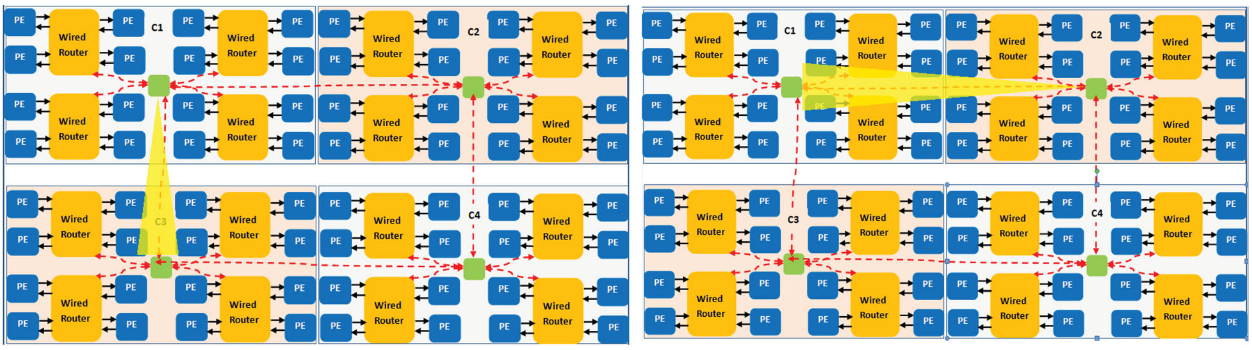

Figure 5. Beam radiated towards the direction of destination core.

optimizing the energy efficiency in WiNoc. For wirelessly transmitting a bit of information from transmitter "*i*" to receiver "*j*", the energy consumed is:

$$E^{tx}{}_{ij} = Pt_{ij}/\ \eta R_b \tag{5}$$

where η is the transmitter efficiency. Considering Equations (3) and (4), Equation (5) can be written as

$$E^{tx}{}_{ij} = [P_r/\ D_t(\varphi_{ij})\ D_r(\varphi_{ji})(\lambda/2\pi R_{ij})^2]/\eta R_b \tag{6}$$

Let ψ_i and ψ_j be a rotation of antenna i and antenna j w.r.t. the die plane, respectively. Thus Equation (3) normalized by the constant terms can be written as

$$E^{tx}{}_{ij} = R^2{}_{ij}/\ [D_t(\varphi_{ij} - \ \psi_i)D_r(\varphi_{ji} - \ \psi_j)] \tag{7}$$

Thus, for minimizing the communication energy from i to j, it needs to determine a rotation ψ_i and a rotation ψ_j such that Equation (4) is minimized. Thus the PF_ABF scheme proactively reduces data flow in all directions while radiating the flow along preferred direction to alleviate congestion and to obtain efficient network performance.

The following steps are used to make an accurate decision for data admission in each node:

Step 1: At a particular instance of time, each node receives a "prflit" *(path response flit)* from its neighbour nodes. At the same time, each node maintains the node_status of its member IHA.

Step 2: The node verifies the node_status to classify the request either as' Admit Data Flow – ADF "or" Reject Data Flow – RDF "for the next clock cycle".

- The request is said to be classified as A_{DF}, provided the request satisfies the pre-defined rule (node_status = = 0).
- The request is said to be classified as R_{DF}, provided the request satisfies the pre-defined rule (node_status = = 1).

Step 3: The requests that are classified as A_{DF} are prioritized and considered as allowable data services (i.e. the node indicates it has available resources for accepting and admitting data flow from or to neighbours). The node reserves resources as per the request. This makes the entire network offer data service accurately and select the most suitable nodes during data admission. Fast route detection and accurate data admission in the proposed model not only enhance scalable hierarchical system design but also lower hardware complexity by simplifying router design.

4. Simulation results and discussion

An experimental model constructed in MATLAB SIMULINK is used to do the experimental study of the suggested PF SDC model. A 64-core system with a single layer or chip is used in the simulator. Figure 6(a) shows the PF SDC system simulation model, whereas Figure 6(b) shows the Router module implementation in the PF SDC model using Simulink. The performance of PF SDC is compared to that of its competitors, which include 2D Mesh, RFI, inter WISE, and SW WiNoC. An experimental model constructed in MATLAB SIMULINK is used to do the experimental study of the suggested PF SDC model. A 64-core system with a single layer or chip is used in the simulator. Figure 6(a) shows the PF SDC system simulation model, whereas Figure 6(b) shows the Router module implementation in the PF SDC model using Simulink. The performance of PF SDC is compared to that of its competitors, which include 2D Mesh, RFI, inter WISE, and SW WiNoC.

In the presence of uniform and non_uniform random traffic, as well as regular and emergency traffic patterns generated by the traffic generator, the effectiveness of the PF SDC model is assessed. With respect to network size and type of traffic in WiNoC, it represents how packet injection streams are divided across the various nodes and how long (traffic hop distance) packets travel from source to destination. Local traffic is defined as traffic that passes through the same layer as the injected data. The packets are originally held in the source node's queue, where they wait to be injected into the network. The faults are injected into the system by deactivating a particular percentage of the wireless links at random. There are 64 flits in each packet. All wired links are the same width as the flit size (32). Input arbitration, routing or switch

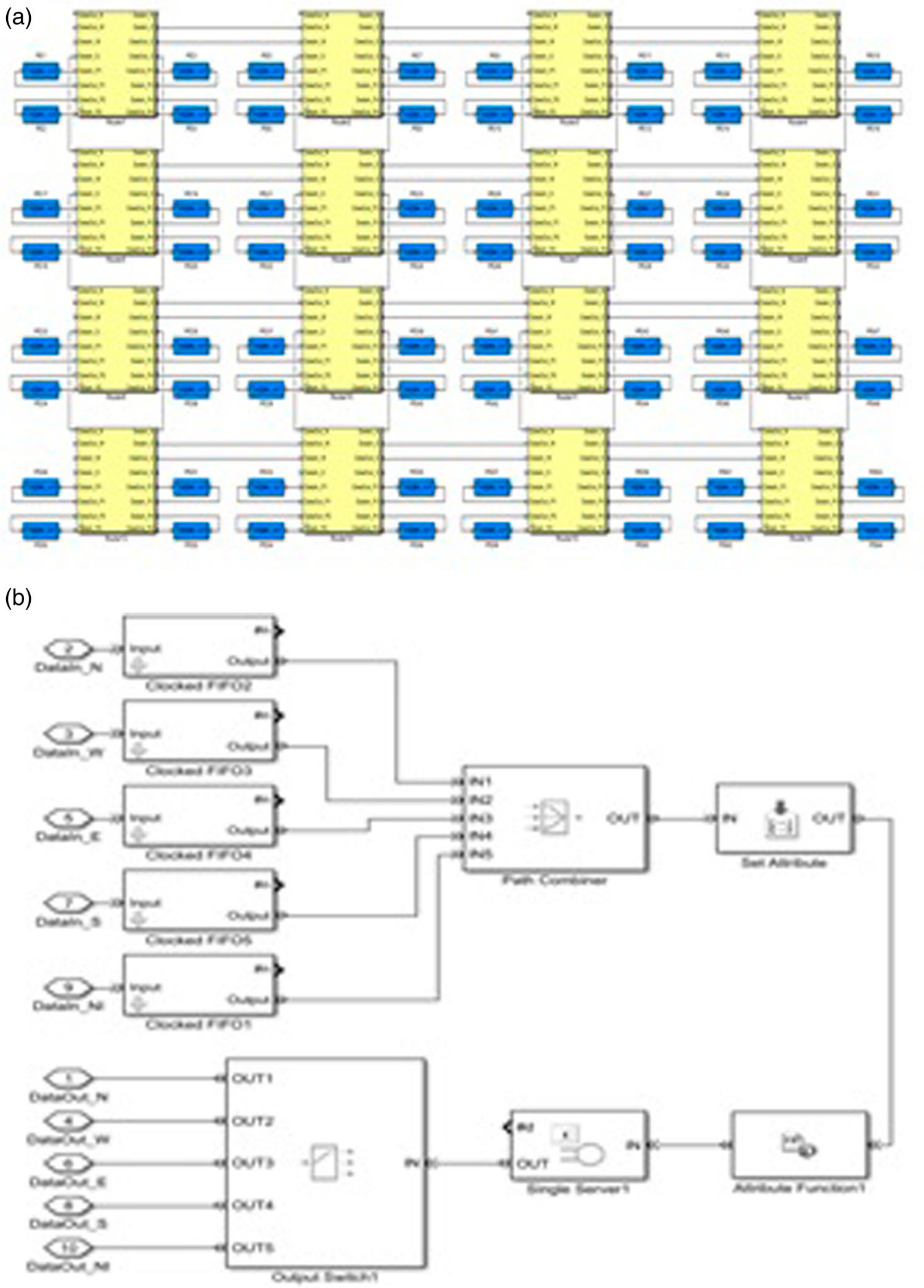

Figure 6. (a) The simulation model of PF_SDC system. (b): Router module of PF_SDC system.

traversal, and output arbitration are the three functional steps of the NoC switch design. Each of the four virtual channels on the input and output ports has a buffer depth of two flits. In wireless networks, routing with flow control utilizing a Fuzzy Inference engine is used in the same way it is in wired links. The NoC switch drives a clock with a frequency of 2.5 GHz. The simulator faithfully simulates the flits' journey through the switches and links per cycle, accounting for both those that reach their destination and those that stall. Each experiment involves a hundred thousand iterations to acquire consistent results. A cycle-accurate simulator is used to assess the progress of data flits every clock cycle, accounting for both flits that reach their destination and those that are dropped. The experimental procedure examines performance metrics such as throughput, latency, attainable bandwidth, power dissipation, and area overhead. For random traffic that is both uniform and not uniform, the PF_SDC model is judged as follows:

4.1 Throughput: The average number of flits successfully received per embedded core every clock cycle is known as throughput. It denotes the amount of data transferred successfully from one node to another in a given amount of time. Figure 7(a) depicts the throughput observed in the presence of a uniform spatial distribution of traffic, while Figure 7(b) depicts non-uniform random traffic (b). Packet Injection Rate is used to

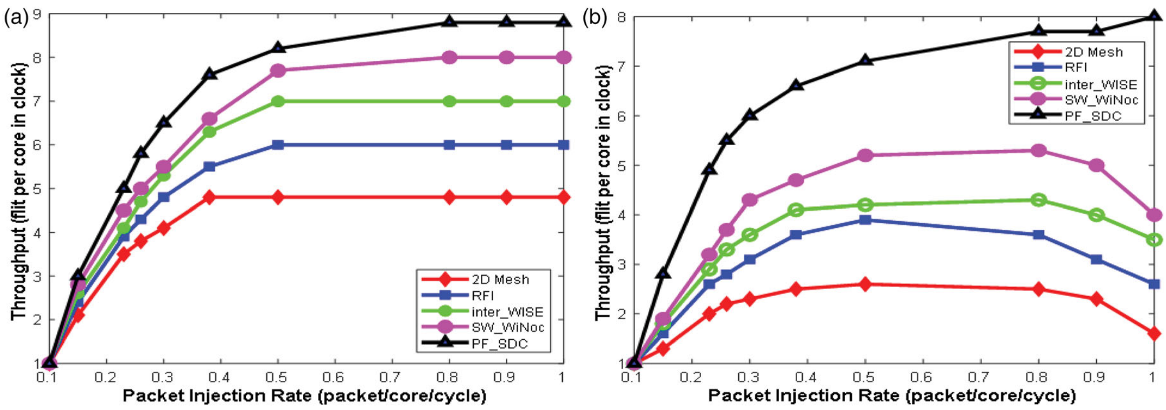

Figure 7. (a) Throughput in uniform traffic. (b) Throughput in non_uniform traffic.

assess throughput (PIR). The number of data packets fed into the network by an IP core is referred to as PIR. It ranges between 0 and 1 in value. PIR = 0.1, for example, means that each node will send 1 packet every 10 clock cycles.

A certain number of cores were assumed to communicate frequently with each other for uniform traffic production. Around half of the traffic is expected to come from the cores and be directed to the other core. In such settings, PF_SDC has a throughput that is roughly ~40–45 percent higher than 2DMesh and more than ~10% higher than its competitors. The advantage of wireless one-hop express links is that it reduces latency, allowing long-distance data transfer to take advantage of wireless links in PF_SDC, resulting in a significant increase in throughput over existing counterparts. The IHA implementation with wireless links connecting the WR ensures data transportation most efficiently via single-hop low-latency communications while preventing each core from travelling large physical distances. A non-uniform random traffic pattern is achieved by allowing many cores to send 20% of traffic originating from them to a single core more frequently. In such a scenario, performance degradation is found in all models at a higher rate than in uniform traffic. This is because the adopted fittest path routing approach, in which packets are routed along the path chosen from source to destination, may result in increased load on a specific link, causing congestion in some situations. It should be noted, though, that even in these situations, the PF_SDC model's performance loss is less than that of its competitors.

4.2 Achievable Bandwidth: The greatest sustainable data rate in the number of bits successfully routed per core per second at network saturation is defined as the peak attainable bandwidth per core. Figure 8 shows the maximum bandwidth per core for various chip configurations when traffic is consistent.

The feasible bandwidth of PF_SDC and SW WiNoC is higher than that of their equivalents, based on the observations. It indicates that systems with wireless links obtain better bandwidth than their wired counterparts. Wireless nodes connect switches inside the chips directly over single-hop links for intra-layer data transfer in the PF SDC paradigm. In other words, when compared to its exclusively wire line intra-chip NoCs equivalents, the PF SDC model with a single chip has better bandwidth. This is because data packets flow from internal cores to peripheral I/O in all wireline I/O-based multi-core systems, such as 2DMesh and RFI, and then route towards intra-layer linkages and travel to the internal cores to the destination layer. PF_SDC has a bandwidth per core of more than ~6Gbps when compared to 2DMesh and more than 5 Gbps when compared to SW_WiNoC. This shows that network I/O-based wireline topologies have the lowest performance since they have numerous switches with I/O modules that allow concurrent communications between neighbouring cores. On the other hand, bandwidth is greatly increased when the cores are set up as clusters and direct IHA-to-IHA wireless connections are made possible in PF_SDC.

4.3 Latency: The flit latency refers to the overall time spent from when the source node injects the header flit into the network until the tail flit is acknowledged by the destination node. The latencies observed in PF_SDC and other models in the presence of uniform and non-uniform random traffic are depicted in Figure 9(a) and Figure 9(b). Models like 2DMesh, RFI, inter_WISE, SW_WiNoC and the proposed PF_SDC exhibit acceptable low latency for the Flit Injection Rate (FIR) of less than 0.2 flit/core/cycle, as shown in the figure. With an increase in injection load, the latency increases. As more flits are held up in the router buffers, latency in all three models, such as 2DMesh, RFI and inter_WISE, is set to increase as FIR increases. Furthermore, when compared to other schemes, the overall delay in 2DMesh and RFI schemes is substantial since the flits in these schemes transit across numerous hubs due to their un-clustered network structure. The suggested technique has a low latency curve since it injects

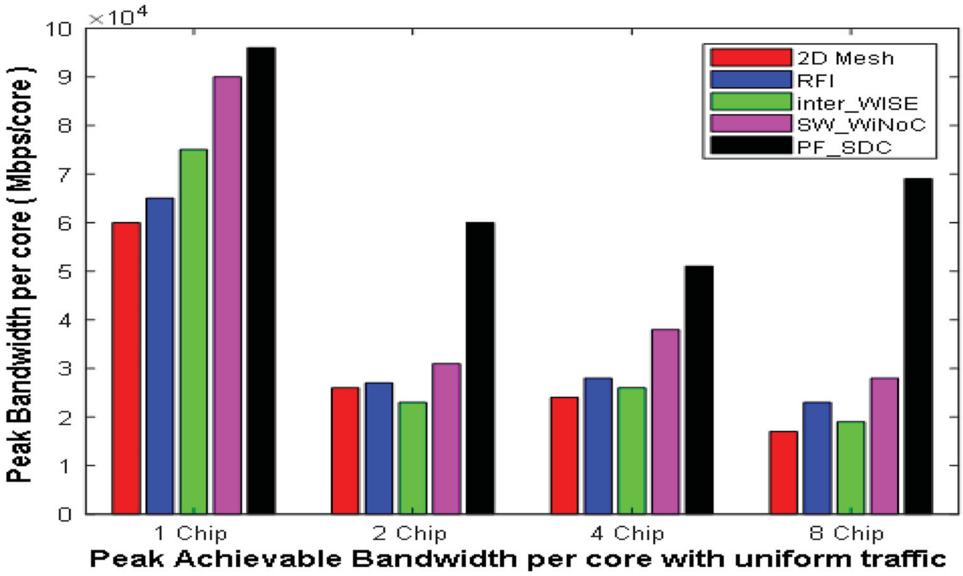

Figure 8. Peak achievable bandwidth per core for different chip configurations under uniform traffic.

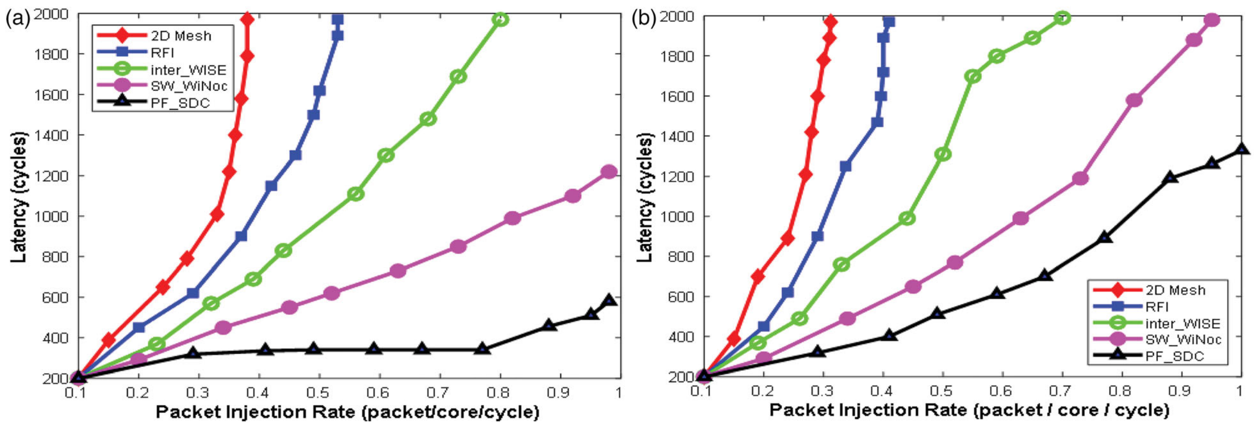

Figure 9. (a) Latency for various models in the presence of uniform traffic. (b) Latency for various models in the presence of non_uniform traffic.

packets along the best path as well as in the direction of the destination via beam formation. Through proactive flow control and fittest path selection, the clustered nature helps to reduce latency by minimizing the number of hops covered by the flits from source to destination. Furthermore, by exceeding the FIR threshold limit, it was discovered that the latency curve in all schemes, including PF_SDC, had a dramatic increase. This is due to the lengthy wait for reserved channels to be released. When the injection load is increased, the PF_SDC scheme shows a regulated latency rise.

4.4 Power Dissipation and Area Overheads: The power usage is measured in nanoseconds using the Simulink tool. Semi-global metal wires were used for the electrical interconnects. In 32 nm technology, the power dissipation of a 128-bit metal connection was estimated to be 23.04 mW/mm at 1 GHz. The power is calculated in an analytical manner for wireless connectivity. In a 10×10 WNoC platform, each core takes up 1 mm^2 of space. The longest diagonal transmission path in such a system is around 7.5 mm. The transmission performance and energy consumption of an on-chip wireless antenna with a transmitter power of −10dBM is 4.5pJ/bit. The number of wired and wireless link traversals, buffer writes, and crossbar traversals for each packet were counted using a cycle_accurate simulator. Each traversal is multiplied by the 128-bit power dissipation that corresponds to it. The power dissipation for various models in the presence of uniform and non-uniform random traffic loads is shown in Figure 10(a). When compared to its SW WiNoc and inter WISE counterparts, the result shows that PF_SDC consumes less power. The reason for this is that flits in the PF_SDC model travel fewer hops utilizing IHA and visit fewer FIFOs, resulting in lower total power usage when compared to other models. Furthermore, the PF SDC saves an average of $\sim$20–30% power compared to all other wireless networks and an average of $\sim$40–50% power compared to all other electrical networks. The suggested model considers low-power wireless communications with a minimal hop network, which results in significant power savings in the PF_SDC design. The power dissipation for a packet to reach its destination wirelessly is less than its comparable cable path

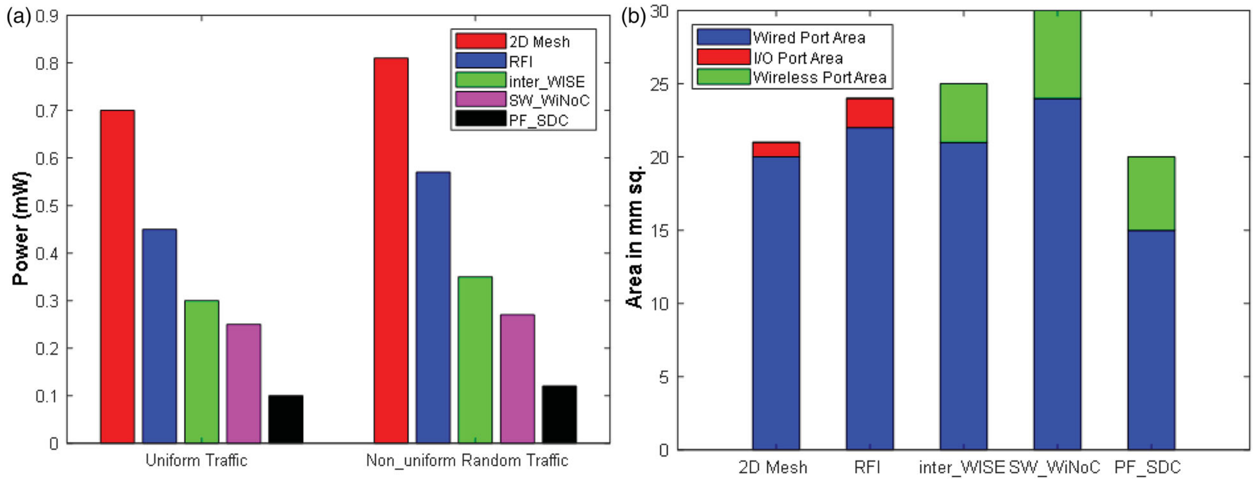

Figure 10. (a) Power dissipation for various models in the presence of uniform and non_uniform traffic. (b): Area overheads of wireline and wireless architectures.

when wireless links are placed properly. Furthermore, PF_SDC has lower power consumption than all other wireless and electrical networks due to the decision-directed traversal of traffic patterns via beam formation. When IHA is used in PF_ SDC, data is transmitted at a distance of less than half the chip. More than 80% of traffic is seen to use wireless networks, resulting in overall power savings of ∼55–60%. When more than ∼90% of wireless links are used for packet traversal, the power savings increase to over ∼70% over 2DMesh. The power consumption of non-uniform random traffic, on the other hand, is slightly higher than that of uniform traffic since the packets traverse at different times.

To measure the performance benefits, the PF_SDC and other existing architectures Area overheads are compared to a wireline 2DMesh. Figure 10(b) shows the area overheads of various wireline and wireless designs. The PF_SDC model, which has a single chip with 64 cores, is compared to its predecessors, as well as a flat wire line 2DMesh system with 64 cores. In contrast to PF_SDC setups, which include wireless links, the 2DMesh includes a number of wired intra-chip links. In the PF_SDC architecture, the number of intra-chip links constrained by transceivers and antennas leads to a lower silicon area overhead. The antennas have very small dimensions, so they take up very little space. According to the investigation, SW_WiNoC has substantially higher overheads since the hubs in each WiNoC subnet take a lot of space because they have a large number of ports to all of the cores in the subnet. The total area overhead of various topologies is calculated by taking into account the area occupied by each transceiver, as shown in Figure 10(b) (an area of 0.3 mm^2). The overall size of the connecting network in wireless multichip systems of the largest configuration is 1.92 percent of the entire system, but the wireless overhead is only 0.46 percent, assuming each chip is 20 mm × 20 mm. Because the number of wireless interconnects per chip stays the same, the fraction of the various area overheads remains the same for other system sizes employing wireless linkages. Because the design includes grouping four cores per router, the wired port area of PF_SDC is lower than SW_WiNoC and inter_WISE. In the PF SDC architecture, this structure decreases the overall space overhead.

5. Conclusion

Despite the NoC's quick advancement and high amount of research activity, practically all study disciplines still have numerous unanswered questions. In this research, we come up with a new model for Wireless NoC systems called "Proactive Flow Control Using Adaptive Beam Forming for Smart Intra-layer Data Communication (PF_SDC)". Using Intelligent Head Agent, the model takes advantage of the hybrid NoC architecture for efficient, high-bandwidth communication. In the face of network dynamics such as fluctuating traffic patterns, the model uses an admission control-based Fuzzy Inference process to dynamically regulate real-time data transmission and appropriately assign resources. In terms of fast throughput, low latency, minimal area overheads, and low power dissipation, simulation findings show that the proposed PF_SDC technique outperforms existing approaches such as 2DMesh, RFI, inter_WISE and SW_WiNoC.

The challenges brought up by the constraints placed on landscape models as well as the interference posed by environmental factors will serve as the foundation for our future study. The foundation of thriving future technologies, in which advanced computing platforms are seamlessly connected to benefit from IoT-based systems in the future, may be considered to be multi-core multi-chip wireless connection architecture. Low-power, high-speed wireless interconnects can also benefit industries like Industry 4.0 and Neuromorphic computing.

Acknowledgement

We would like to thank our colleagues from our institution for providing deeper insights and expertise that helped our research to great extent.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

There are no funding resources available for this work.

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