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Fuzzy Logic Medium Access Controller Mechanism in WiNoC (FLMAC-WiNoC): Enhancing System Performance and Improve Energy Efficiency

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ABSTRACT

Wireless Network-on-Chip (WiNoC) has gained significant attention as a viable solution for interconnecting multi-core Systems-on-Chip (SoCs) due to its advantages in power efficiency, scalability, and flexibility. Advancement in WiNoC technology with increase in the number of radio hubs, requires an effective medium access control (MAC) strategy to enhance energy efficiency and improve the entire system performance. However, to efficiently managing the wireless medium in a WiNoC is a challenging task due to its shared nature and susceptibility to interference. Addressing these challenges, researchers have explored various MAC mechanisms, among is the implementation of the fuzzy logic MAC mechanism, that has shown promising results. A key limitation of the existing MAC techniques in WiNoC architectures is the lack of mechanisms to reduce energy consumption by dynamically adjusting the data transmission rate of the radio hubs. This paper proposed a Fuzzy Logic Medium Access Controller Mechanism in WiNoC (FLMAC-WiNoC) that uses a fuzzy logic controller that dynamically changes the data transmission rate according to the traffic characteristics. A cycle-accurate noxim simulator was used for the experiments and the results shows that FLMAC-WiNoC reduces energy consumption by 48.5%, reduce latency by 25%, improve channel utilization by 88.5% and throughput by 1.2 Gbps compared to existing techniques.

INTRODUCTION

Wireless Network-on-Chip (WiNoC) is a promising technology that aims to address the communication challenges in multi-core systems-on-chip (SoCs) (Benini & De Micheli, 2002). It provides a wireless communication infrastructure that replaces traditional wired interconnects, offering increased flexibility, scalability, and reduced power consumption. To efficiently manage the wireless medium in a WiNoC, a suitable medium access control (MAC) mechanism is required (Rusli *et al.,* 2025; Fasiku, *et al.,* 2019). Fuzzy Logic MAC (FLMAC) is an innovative approach that has gained attention for its ability to adaptively allocate resources based on the dynamic network conditions (Deb *et al.,* 2012; Mansoor, N., & Ganguly, 2015; Matolak *et al.* 2012). In the advancement of multi-core System-on-Chip (SoC), power and complexity are the two major bottlenecks for processor technology scaling (Benini & De Micheli, 2002; Abadal *et al.,* 2018). The last decade has seen a significant increase in multi-core systems, and wireless interconnects have been proposed to alleviate single-hop links between distant cores in the chip (Rad *et al.,* 2020). However, this technology opens up new opportunities for detailed investigations into the design of the wireless NoCs; it is an emerging technology and a paradigm shift from multi-core to the many-core system era (DiTomaso *et al.,* 2014). WiNoCs are composed of multiple wireless routers connected through wireless links. These routers facilitate communication between the cores within a multi-core SoC (Rad *et al.,* 2020; DiTomaso *et al.,* 2014). The MAC mechanism in a WiNoC is responsible for coordinating access to the wireless medium, ensuring fairness, avoiding collisions, and optimizing the overall network performance (Rusli *et al.,* 2025). However, to efficiently manage the wireless medium in a WiNoC is a challenging task due to its shared nature and susceptibility to interference. The focus has shifted from increasing the core frequency to integrating more cores within the same chip. As the number of cores increases, the major challenge is the efficient intra-chip communication among the cores. Although wired connections have worked well for a moderate number of cores, but with the wireless communication, it has typically shown better performance (Fasiku *et al.,* 2021; Fasiku *et al.,* 2020).

Existing works on WiNoC from the literatures reviewed focused on different aspects, such as transceiver design (Fasiku *et al.,* 2021; Abadal *et al.* 2015; Sherwood *et al.,* 2004), channel modeling (Abadal *et al.* 2015; Sherwood *et al.,* 2004) and network architecture (Sherwood *et al.,* 2004; Sodhro *et al.* 2018). This paper focuses on the problem of MAC in WiNoCs. the existing literature on MAC for WiNoCs can be categorized as static bandwidth allocation techniques and random-access techniques (Soteriou *et al.,* 2006; Abadal *et al.,* 2019). The former is based on dedicated orthogonal channels with time, frequency, or code-multiplexing. Although this strategy provides high throughput, the network utilization is sub-optimal for variable workloads (Sherwood *et al.,*

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2004). To overcome these challenges, researchers have explored various MAC mechanisms. One innovative approach is the implementation of Fuzzy Logic MAC mechanism, which leverages fuzzy logic to dynamically allocate wireless channel resources based on system parameters and network conditions (Soteriou *et al.,* 2006). The traditional MAC protocols, such as Time Division Multiple Access (TDMA) (Matolak *et al.* 2012; Fasiku *et al.,* 2020) or Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) (Garcia-Luna-Aceves, 2017), are not well-suited for WiNoC due to the dynamic nature of wireless channels and varying traffic patterns. Fuzzy Logic MAC, on the other hand, leverages fuzzy logic principles to make intelligent decisions based on imprecise and uncertain information, making it suitable for the complex and changing wireless environment (Soteriou *et al.,* 2006; Abadal *et al.,* 2016; Sherwood *et al.,* 2004; Sodhro *et al.,* 2018).

Moreover, the hardware complexity of static bandwidth allocation schemes increases with the number of nodes. At the other extreme are random access techniques such as CSMA. Although random access techniques have the advantage of high bandwidth utilization, it is a well-known fact that random access techniques suffer from serious scalability issues due to collisions in high node density scenarios. Therefore, one of the popular techniques for WiNoC MACs is coordinated access control using token passing. The existing works on token passing MACs for WiNoCs either combine token passing with channelization techniques (Sodhro *et al.,* 2018) or random-access techniques (Fasiku *et al.,* 2021). However, these techniques result in sub-optimal performance in many-core scenarios, mainly because of the absence of performance and traffic-aware scheduling. Unlike other wireless networks, energy consumption is directly related to heat dissipation, which harms chip performance (Deb *et al.,* 2012; Abadal *et al.,* 2016).

This paper focuses on the problem of designing a MAC for WiNoCs, which not only provides low latency but also reduces the rate of energy consumption, improve channel utilization and throughput. The proposed FLMAC-WiNoC uses a fuzzy logic controller to dynamically adjust the nodes' data transmission rate in a WiNoC according to the traffic characteristics (Zhang *et al.,* 2005). The research put into consideration the number of active nodes with the available traffic at each node, to adjust the data transmission rate. The proposed fuzzy logic controller assigns a penalty for each time unit that an active core has to wait to transmit its data. Moreover, to reduce energy consumption, a penalty is introduced for each available data rate, with a higher penalty for higher data rates. Using a token passing scheme with a maximum hold interval, all the cores in the WiNoC transmit their data (Fasiku *et al.,* 2019). Hence, the propose a fuzzy logic controller would dynamically changes the data transmission rate with respect to the network traffic characteristics. The performance evaluation of the proposed methods was done using various synthetics traffic patterns and application trace (splash/parsec). Our simulation results show that the proposed techniques improve network performance.

The rest of this paper is structured as follows. Section II reviews the related works. Section III presents system model and methodology deployed in the research. The proposed fuzzy logic based on MAC technique were discussed in section IV. Section V presents the proposed FLMAC operation. Section VI presents the results and discussion. The conclusion of the paper is in section VII with recommendations for future works.

LITERATURE REVIEW

Several studies (Abadal *et al.,* 2018; Fasiku *et al.,* 2021; Palesi *et al.,* 2015; Fasiku *et al.,* 2019), have focused on MAC mechanisms for WiNoCs to improve the system performance. There are different traditional types of MAC developed in the literature to actualized its efficiency, such as simple and distributed MAC mechanisms ALOHA (Abramson *et al.,* 1970; Kuo, 1974), Carrier Sense Multiple Access (CSMA) (Garcia-Luna-Aceves, 2017). Token based-time Division Multiple Access (TDMA) (Matolak *et al.,* 2012; Fasiku *et al.,* 2020), a Token-passing based Time Division Multiple Access (T-MAC) (Garcia-Luna-Aceves, 2017; Catania *et al.,* 2016), Code Division Multiple Access (CDMA) (Choi *et al.,* 2013) is based on MAC that implements parallel communication between wireless interface (WIs). However, the CDMA-based MAC mechanism requires overhead for maintaining synchronization and maintains orthogonality between code channels; hence, this MAC mechanism makes transceiver design extremely difficult. While these mechanisms provide different advantages, they may suffer from drawbacks such as suboptimal resource utilization, unfairness, and high energy consumption. The Fuzzy Logic MAC mechanism offers a novel approach to overcome these limitations (Deb *et al.,* 2012). It leverages fuzzy logic principles to dynamically allocate wireless channel resources based on real-time network conditions and system parameters. By considering factors such as channel quality, traffic load, distance, priority, and energy consumption (Benini and De Micheli, 2002; Deb *et al.,* 2012; Mansoor and Ganguly, 2015; Matolak *et al.,* 2012).

Most existing energy-efficient MAC techniques for wireless networks rely on switching the transceiver on and off based on traffic characteristics. However, such an on/off strategy is not suitable for Wireless Networks-on-Chip (WiNoCs) because, unlike conventional wireless networks, chip cores must maintain high availability (Fasiku *et al.,* 2020; Lit *et al.,* 2024). Recent studies have also revealed that WiNoC traffic is highly heterogeneous. Abadal *et al.,* (2015) and Soteriou *et al.,* (2006) demonstrated that, in addition to unicast communications, global and multicast flows constitute a significant portion of WiNoC traffic. Similarly, Abadal *et al.,* (2016) and Sherwood *et al.,* (2004) reported that the wide variety of applications running on a system leads to greater variability in communication demands and traffic patterns compared with conventional wireless networks. Based on their observations, this paper proposes an adaptive data transmission rate MAC protocol for WiNoCs. Generally, there are two main approaches to reducing the energy consumption of a radio subsystem: controlling the transmission power or adjusting the data transmission rate. However, previous studies have shown that controlling the data transmission rate achieves greater energy savings than power control (Palesi *et al.,* 2015; Zhang *et al.,* 2005; Fasiku *et al.,* 2023). Therefore, this work adopts data transmission rate control as a strategy to reduce energy consumption in WiNoCs.

Existing studies from Deb *et al.,* (2012); Matolak *et al.,* (2012) and Zhang *et al.,* (2005) apply fuzzy logic in the domain of Network-on-Chip (NoC) primarily focus on using the buffer state of nodes to prevent congestion in routing algorithms. For example, Ebrahimi *et al.,* (2013) proposed an adaptive routing algorithm for NoCs based on a fuzzy logic controller that utilizes the buffer state at nodes to estimate congestion levels. This approach optimizes routing by distributing traffic through less congested routers. Experimental results indicate that the fuzzy-based routing scheme enhances overall system performance. Similarly, Dehyadegari *et al.,* (2011) introduced a fuzzy logic controller for NoC routing that uses both buffer state and packet waiting time as input parameters. In this approach, link costs are dynamically determined according to the current network conditions. The fuzzy-based adaptive routing algorithm effectively manages traffic distribution and redirects packets toward less congested nodes, thereby improving network performance with minimal hardware overhead. Alaei and Yazdanpanah (2019) also proposed a fuzzy-based adaptive routing algorithm for NoCs using a honeycomb topology. Their method introduces a livelock- and deadlock-free routing algorithm based on fuzzy logic for hexagonal zones within a flat triple coordinate system. Simulation results demonstrate that the proposed algorithm achieves improved performance in terms of latency, power consumption, throughput, and chip area in NoC architectures.

The existing literature for WiNoC MACs is not exhaustive, and we discuss some of the recent techniques. DiTomaso *et al.,* (2014) proposed the use of energy-efficient wireless transceivers along with dynamic channel assignment based on bandwidth demand. In their approach, an adaptive algorithm operates in the background, while a token-based sharing scheme is employed to efficiently utilize the available wireless bandwidth. Also, Mansoor *et al.,* (2016) introduced a history-based predictor designed to estimate the bandwidth requirements of network nodes. The authors propose the design of two dynamic MAC mechanisms that can dynamically allocate time slots to each token-based WIs based on a predicted estimate of the demand. The authors claimed that their TDMA based MAC could outperform a token-based MAC in energy efficiency and sustain higher data bandwidths (Mansoor and Ganguly, 2015). Palesi *et al.,* (2015) proposed a similar token-passing approach known as the Radio Access Control Mechanism (RACM) for Wireless Network-on-Chip (WiNoC) architectures. RACM aims to improve both performance and energy efficiency in WiNoCs. The mechanism operates through a token-based scheme in which a token circulates among radio hubs, allowing the hub that holds the token to access the wireless medium for a specific number of clock cycles. The key idea behind RACM is to redistribute unused clock cycles from the previous round among the radio hubs in proportion to how effectively they utilized the radio medium. This strategy helps to reduce communication delay and improve resource utilization.

Moreover, Mansoor *et al.* (2016) proposed a dynamic Medium Access Control (MAC) mechanism that establishes wireless links based on traffic demands while minimizing overhead. This interconnection approach integrates wireless links into the NoC fabric to better address traffic non-uniformity and temporal variations in communication patterns. In their design, a hybrid MAC scheme is introduced, which uses Carrier Sense Multiple Access (CSMA) during periods of heavy traffic load and switches to a token-based MAC scheme when the traffic load is low. However, many of the existing techniques rely on complex traffic prediction mechanisms, making them computationally expensive. In addition, they often fail to consider traffic diversity in MAC design for WiNoCs. To address these limitations, this paper proposes an adaptive data transmission rate mechanism, an aspect not adequately considered in previous works. The proposed approach reduces latency and improves the energy efficiency of WiNoCs by employing a rule-based fuzzy logic controller that dynamically adjusts the data transmission rate according to network traffic characteristics.

MATERIALS AND METHODS

Fuzzy Logic is a mathematical framework that deals with imprecise and uncertain information. It is particularly suitable for systems that require decision-making in complex and uncertain environments. The Fuzzy Logic MAC mechanism employs fuzzy logic principles to efficiently allocate wireless channel resources in a WiNoC. In a WiNoC, multiple cores or processing elements communicate with each other using wireless links. The FLMAC mechanism aims to regulate access to these wireless links, ensuring fairness, avoiding collisions, and maximizing throughput. It achieves this by considering several input parameters, such as channel quality, traffic load, distance, priority, and energy consumption, by applying fuzzy logic rules to determine the appropriate channel allocation.

The diagram in Figure 1 shown the proposed system model for this work. A set of cores were connected to the centralized FLMAC-WiNoC controller wirelessly and each core may have a wire connection but, we assume that each core can only communicate through its wireless interface.

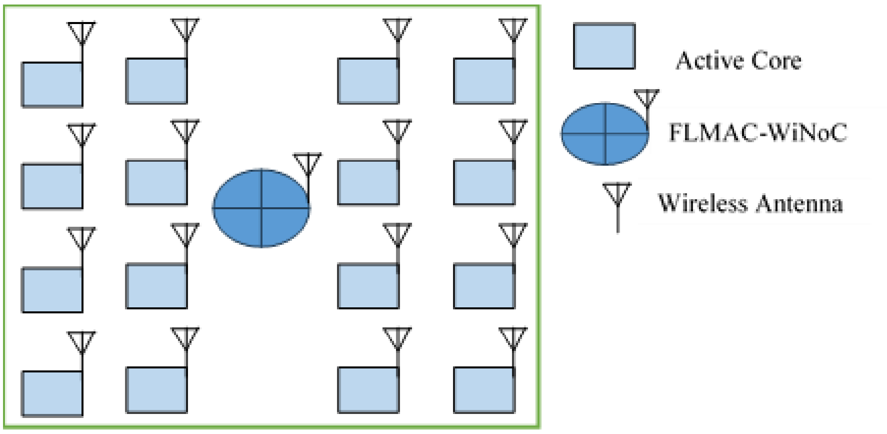


Figure 1: A WiNoC System Interface Model

Implementation of Fuzzy Logic MAC in WiNoC

The implementation of FLMAC mechanism in WiNoC offers several advantages. Firstly, it provides adaptability to the dynamic wireless environment and enabling efficient resource utilization. Secondly, it enhances fairness by considering various factors and avoiding monopolization of the wireless medium by certain nodes. Lastly, it allows for intelligent decision-making based on imprecise and uncertain information, making it suitable for real-world scenarios.

However, implementing FLMAC in WiNoC also poses some challenges. Designing an efficient fuzzy inference system (FIS) requires domain knowledge and expertise to define the appropriate linguistic variables, membership functions, and fuzzy rules. Also, optimizing the FIS parameters and rules can be complex and time-consuming. Additionally, the computational overhead of fuzzy inference may impact the overall system performance and energy consumption.

Implementation of FLMAC in WiNoC involves the following key components:

1. Fuzzy Inference System (FIS): The heart of the Fuzzy Logic MAC mechanism is the FIS, which consists of a set of linguistic variables, membership functions, fuzzy rules, and an inference engine. The linguistic variables define the inputs and outputs of the FIS, such as channel occupancy, traffic load, and fairness. Membership functions map the crisp input values to fuzzy sets, representing the degrees of membership. Fuzzy rules define the relationships between the inputs and outputs, capturing the expert knowledge or learning from training data. The inference engine applies these rules to determine the appropriate output values.

2. Channel Occupancy Estimation: Accurate estimation of channel occupancy is crucial for efficient resource allocation in WiNoC. FLMAC employs techniques such as energy detection or signal-to-noise ratio (SNR) estimation to measure the channel occupancy. The obtained channel occupancy values are then fuzzified and used as inputs to the FIS.

3. Traffic Load Monitoring: Monitoring the traffic load in the network is essential to ensure fairness and avoid congestion. Fuzzy Logic MAC uses various metrics, such as packet arrival rate, packet size, and queue length, to estimate the traffic load. These metrics are fuzzified and fed into the FIS to determine the appropriate action, such as adjusting the data transmission and enhance evenly data distribution for the radio-hub.

4. Adaptive Resource Allocation: FLMAC dynamically allocates resources, such as time slots or data transmission, based on the inputs from the channel occupancy estimation and traffic load monitoring. By considering the uncertainties and imprecisions in the network conditions, the FIS makes intelligent decisions to optimize the resource allocation, maximizing throughput and minimizing latency.

5. Fairness Enhancement: Fairness is a crucial aspect of the FLMAC protocols, ensuring that all nodes have a fair chance to access the wireless medium. FLMAC incorporates fairness as an important objective by considering factors such as RH priorities, cores distance apart, traffic characteristics, and previous access history. The fuzzy rules within the FIS guide the resource allocation process to maintain fairness among competing nodes.

FLMAC-WiNoC Mechanism Development

The problem formulation addressed by the FLMAC-WiNoC mechanism is to efficiently allocate wireless channel resources in a WiNoC, taking into account various system parameters and network conditions. The objective is to enhance efficiency, fairness, collision avoidance, and energy consumption, while maximizing the utilization of the wireless medium.

Let us denote the total latency for nodes waiting to transmit their data by L and the total energy consumed by the WiNoC per unit time as E. Note that L depends on the number of active cores α and the amount of -traffic that each core needs to send τi for i = 1, 2, - - - -, N total cores. For example, a large number of active cores with large τi values will increase the latency. Let us introduce a penalty for a core waiting to transmit its data, i.e., a penalty of PL per unit time is
incurred for each core waiting to transmit its data. Then, if there are $\alpha(ti)$ cores waiting at time ti for th time units to transmit their data, then the total cost of waiting at

time PW(ti) is given by:

PW(ti) = α(ti) × PL × th. ------------------------------ (1)

Similarly, E depends on the transmission rate r of data, i.e., a higher transmission rate will result in more energy consumption and vice versa. Let, introduce a penalty for transmitting at a specific data rate. For example, consider a set of different possible data rates μ = [μ1, μ2, μ3, - - - - - -, μm]T, then, the penalties are r = [r1, r2, r2, - - -rm]T, where μ1 ≤ μ2 ≤ μ3 ≤ · · · ≤ μm and r1 ≤ r2 ≤ r3 ≤ · · · ≤ rm. Hence, a higher data rate resulted into more energy consumption and incurs a higher penalty. If a WiNoC has been transmitting at a data rate of μ(ti) ∈ μ for a time duration of tr time units, then the total energy cost is given by:

PE(ti) = rμ(ti) × tr -------------------------- (2)

The total cost P, at time ti is then given by:

J(ti) = PW(ti) + PE(ti) ------------------------------ (3)

The Fuzzy Logic Based on MAC TechniqueThe Fuzzy Logic Based on MAC Technique

This section presents the proposed FLMAC technique for WiNoC based on a fuzzy logic controller. The steps involved in designing the fuzzy logic–based medium access control are outlined as follows:

Fuzzification

The FLMAC proposed has two fuzzy inputs, i.e., the current data rate k = rμ(ti) and the waiting cost per unit time for the current number of active nodes h = PLα(ti). The universe of discourse for the fuzzified variables k and h are [0 6] and [0 ∞], respectively. The corresponding membership functions are given in Figure 2. These membership functions were chosen based on the best performance among various candidates in a number of numerical experiments carry out with different problem instances (Ebrahimi *et al.,* 2013; Shahbazova *et al.,* 2020). Each input is represented by four linguistic values, zero (ZO), positive small (PS), positive medium (PM), and positive big (PB). Thus, this results in 42 = 16 rules in the rule base.

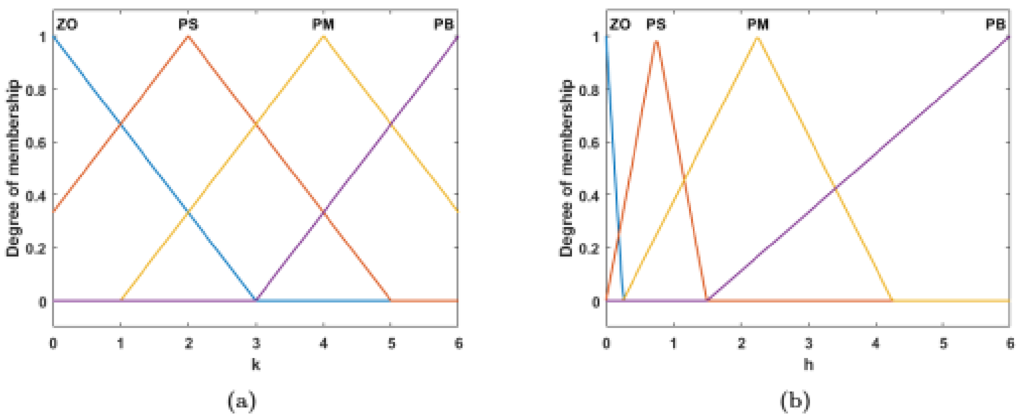


Figure 2: Input membership functions: (a) k; (b) h

The output of FLMAC is a control signal that either increases or decreases the data rate based on the system's current state, i.e., the number of active nodes and the current data rate. Using the standard domain [-6 6] for fuzzy outputs as the universe of discourse for the output Δk. Note that Δk is the incremental control of the data rate. Thus, the new data rate is calculated at each time step by adding Δk to the current data rate k. The membership function for the output Δk is shown in Figure 3. Δk is represented by seven linguistic values, negative big (NB), negative medium (NM), negative small (NS), zero (ZO), positive small (PS), positive medium (PM), and positive

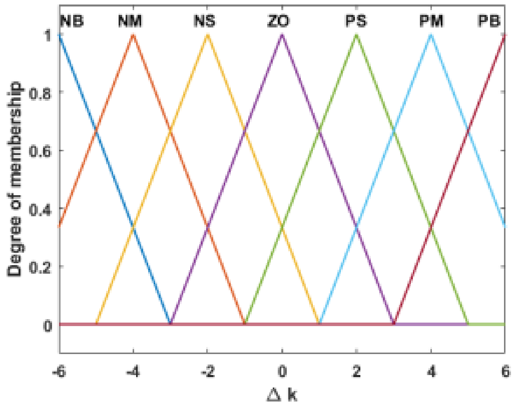


Figure 3: Output membership function: Δk

big (PB).

Knowledge Base

In developing the knowledge base for FLMAC, we first observe the following:

1. If there are no active cores, and the transmission rate is minimum k = µ1, then the transmission rate should not be changed.

2. If there are no active cores and the transmission rate is maximum k = µm, then the transmission rate should be reduced to the minimum µ1, i.e., the variation of data rate Δk should be negative big.

3. If all the nodes are active and the transmission rate is maximum µm, then the transmission rate should not be changed, i.e., Deltak should be ZO.

Table 1: Rule Base for FLMAC

Rule	h	k	Δk	Rule	h	k	Δk
1	ZO	ZO	ZO	9	ZO	PM	NM
2	PS	ZO	PS	10	PS	PM	NS
3	PM	ZO	PM	11	PM	PM	ZO
4	PB	ZO	PB	12	PB	PM	PS
5	ZO	PS	NS	13	ZO	PB	NB
6	PS	PS	ZO	14	PS	PB	NM
7	PM	PS	PS	15	PM	PB	NS
8	PB	PS	PM	16	PB	PB	ZO

Using a similar approach, we obtain the rule base in Table 1.

Inference Engine

The process by which the input rules given in Table 1 are combined to produce a control output is called the inference engine. Based on the popular Mamdani implication (Alaei and Yazdanpanah, 2019; Izquierdo and Izquierdo 2017), we used the individual rule firing inference engine Ebrahimi *et al.,* 2013; Shahbazova *et al.,* 2020). The inference engine fires each rule individually, and then the control output is computed by taking the minimum of the degree of membership of each input.

Defuzzification

The action of converting fuzzy control actions into nonfuzzy (or crisp) ones is called defuzzification. For example, the consequences "Δk is PS with grade 0.7458" and "Δk is PM with grade 0.1450" cannot be used in practice. Therefore, these consequences must be converted into a crisp value, i.e., Δ*k = - (m - 1) - (m - 2) · · · - 101 · · · - (m - 1) which can be added to the current data rate k. To achieve this, the most widely used defuzzification technique, known as the height method, is applied. In this approach, the peak value ei for each consequence is obtained from the output membership function. Using the membership grade value fi associated with each consequence, the crisp output value is calculated as:

$$\Delta_k^* = \frac{\sum_{i=1}^{k} e_i f_i}{\sum_{i=1}^{k} f_i}. \quad \text{------------------------------} \ (4)$$

The Proposed FLMAC-WiNoC Controller

The overall block diagram of the proposed MAC fuzzy logic controller is shown in Figure 4. Here, the controller's main function is to control the data transmission rate according to the active cores and traffic availability, i.e., the objective function in (3F) is minimized to reduce the latency and the energy consumption of FLMAC.

In each time interval, FLMAC-WiNoC uses token passing with a maximum limit when a core can hold on to the token, i.e., a core can send all the data it has been holding up until the current time interval. The operation flow-chart of FLMAC is shown in Figure 5, and the required steps stated as follows:

i. All the active cores send a reservation request to FLMAC-WiNoC. These requests are received by passing a token over every node in a round-robin fashion. Note that this does not degrade the performance of FLMAC-WiNoC because none of the cores can hold the token for a long time. They need to convey the size of the data they want to transfer. Therefore, the latency will be negligible at each node.

ii. The system parameters h and k are initialized after obtaining the reservation request from all the cores. The cores which have data to transfer are added to the set of active cores.

iii. The system invoked h and k as the inputs, which gives an output for the optimal incremental change in the current data rate, and we obtain the optimal data rate knew.

iv. A token-passing MAC is used in a round-robin fashion over all the active nodes. All the cores transmit their data using the new rate knew. In this research, the standard token passing with maximum hold time is used. For example, for a WiNoC mesh size of 4 × 4, the round-robin token passing over active nodes, as shown in Figure 6.

v. After one complete round of the token over the active cores, new reservation requests are obtained, and the system parameters are updated according to the new reservation requests.

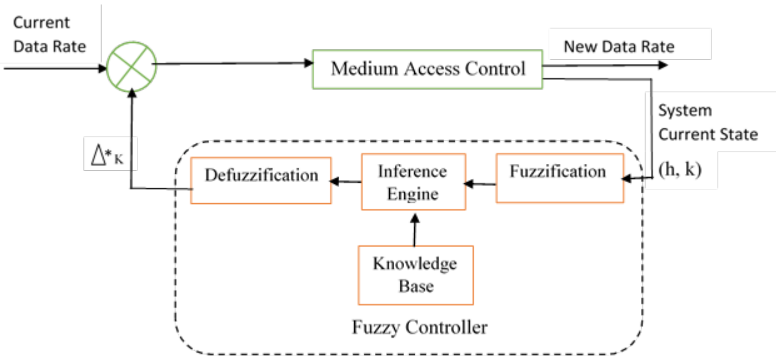


Figure 4: Block diagram of fuzzy logic MAC

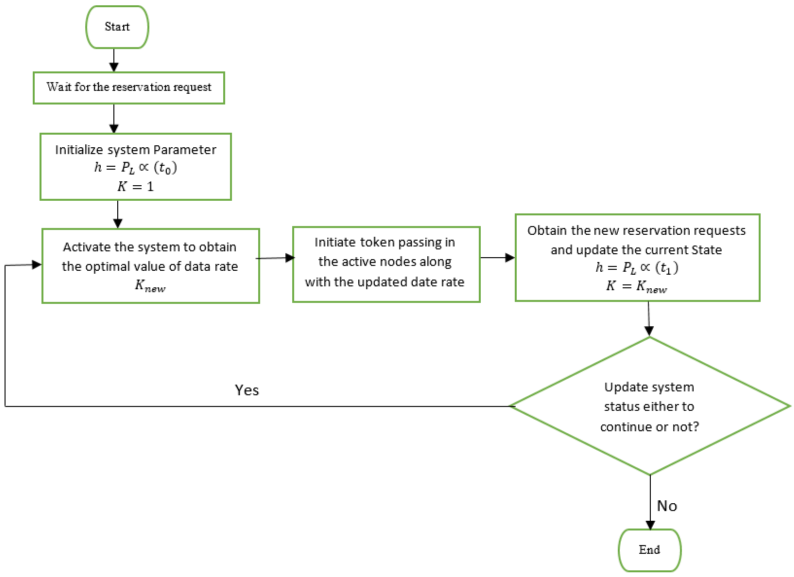


Figure 5: Operation of FLMAC

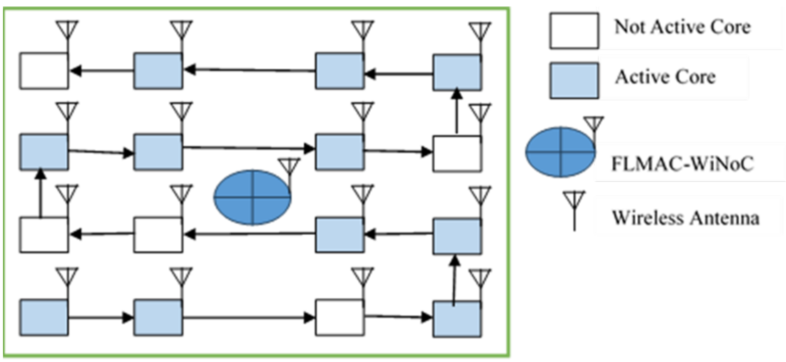


Figure 6: Round Robin Token Passing Architecture

RESULTS AND DISCUSSION

This section discusses the experiments conducted on the cycle-accurate Noxim simulation (Catania *et al.,* 2016; Catania *et al.,* 2015). The Noxim simulation was configured using the parameters given in Table 2. The most important performance metrics putting into consideration for WiNoC using FLMAC techniques are latency, throughput, channel utilization, packet delivery ratio and energy consumption. Although energy is not considered a scarce resource, however, energy consumption is important due to the heating caused by its dissipation. Note that heat dissipation needs to be lower in many-core designs to maintain optimal performance and elongate the chip life span. Thus, in this section, the performance of FLMAC would be evaluated based on latency and energy consumption; a lower value for both is considered better. The parameters related to these two-performance metrics are the mesh network size and the traffic rate. Therefore, the performance of WiNoC was

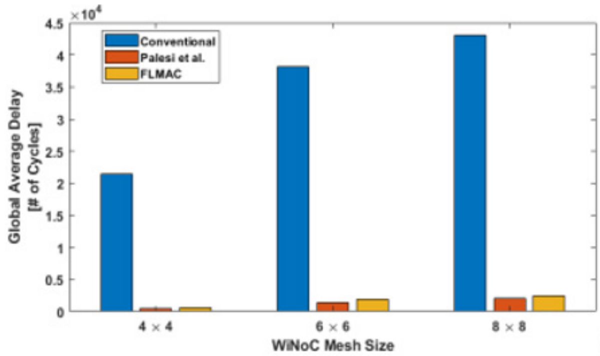
Table 2: Noxim Configuration

Parameter	Value
Mesh Dimension	4x4, 6x6, 8x8
Flit size	32 bits
Routing algorithm	XY
Traffic distribution	Random
Packet Size	4 - 16 flits
Clock Period	(1 cycle) 1000 ps
Clock Frequency	1 GHz
Reset Time	1000 Cycles
Simulation Time	100,000 Cycles
Wireless Channels	1
Hub-tile buffer size	8 flits

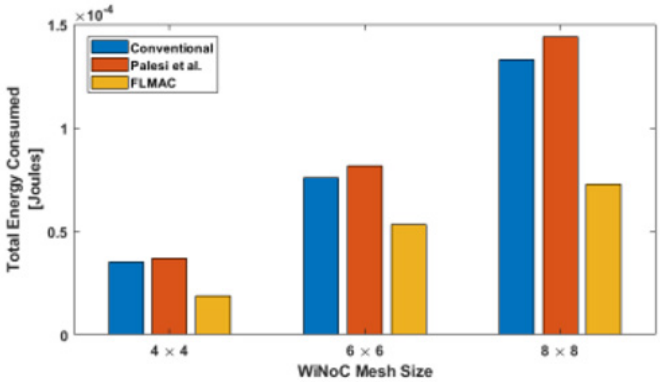
evaluated using three WiNoC node architectures, i.e., 16, 36, and 64 node square mesh networks, and three packet injection rates (PIR) to signify low, medium, and high traffic scenarios.

FLMAC would be compared with two existing techniques; first, the conventional method where the wireless transmitting hub node holds the channel for a specific period for flits of the transmission of the packet, and secondly, the technique proposed by Palesi *et al.,* (2015). The conventional method serves as the baseline, while the technique proposed by Palesi *et al.,* (2015) is one of the existing technique for efficient MAC application in WiNoCs. The simulation run-time was kept constant at 100,000 cycles, where each cycle is equal to 1 nano-second (Matolak *et al.,* 2012). Note that the conventional method and Palesi *et al.,* (2015), always transmit at the maximum data rate of 32 Gbps. In contrast, FLMAC transmits at four data rates of 8, 16, 24, and 32 Gbps, depending on the active cores and available traffic. The maximum hold count (MHC) for Palesi *et al.,* (2015) and FLMAC was kept constant at 8 as, on average, 8 clock cycles are found to be enough for a radio hub to completely drain a packet. The latency was obtained by recording the global average delay (GAD) in cycles, and the energy consumption was recorded in Joules. Next, we evaluate the performance of FLMAC at varying traffic rates, i.e., low traffic rate, medium traffic rate, and high traffic rate with 0.01, 0.05, and 0.1 packet injection rates in Noxim, respectively. These traffic rates correspond to 1 packet injection per 100 cycles, per 20 cycles, and per 10 cycles, respectively.

Figure 7(a) shows the latency of FLMAC, the conventional method, and Palesi *et al.,* (2015) when λ = 0:01. It was observed that the average latency of the proposed technique and the technique proposed by Palesi *et al.* are approximately the same. However, the conventional method results in approximately 90% more latency than FLMAC. Figure 7(b) presents the energy consumption in the three techniques. It is observed that the conventional and Palesi *et al.* consumed 45% and 49% more energy as compared to FLMAC for all three WiNoC mesh sizes. Thus, FLMAC outperforms the existing techniques in terms of energy consumption. Note that although the latency of Palesi *et al.* was approximately the same as FLMAC, FLMAC can achieve the same latency with significantly lower energy consumption. The same trends



(a)



(b)

Figure 7: Low Traffic Rate, λ = 0:01: (a) Latency; (b) Energy Consumption

are observed for medium traffic rate λ = 0.05 and high traffic rate λ = 0.1, shown in figures 8 and 9, respectively. FLMAC results in approximately 30% and 35% lower energy consumption in medium and high traffic than existing techniques.

To gain further insight into the effect of traffic rate, we plotted the energy consumption of each technique against λ in Figure 10(a). This figure indicates the superior performance of FLMAC. Note that the energy consumption of FLMAC changes with the traffic rate, i.e.,

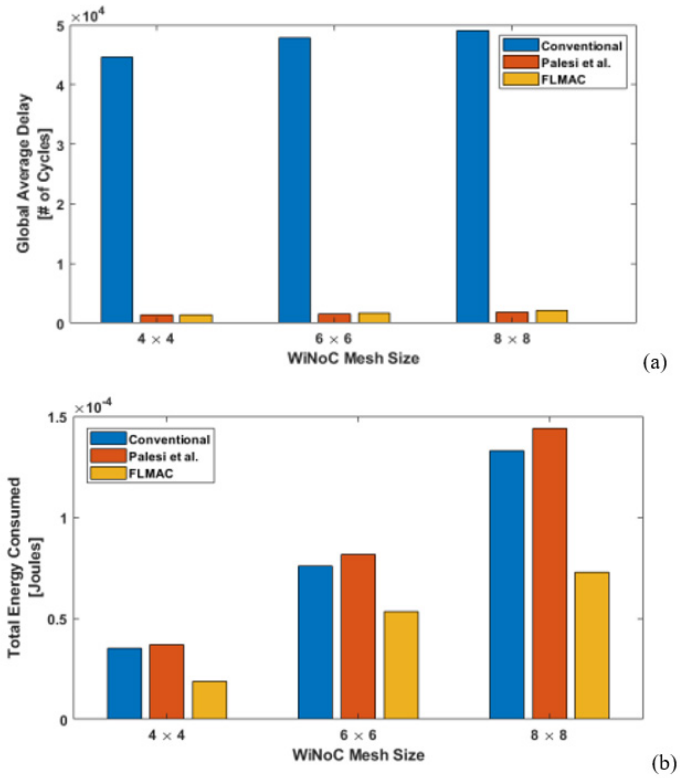


Figure 8: Medium Traffic Rate, λ = 0:05: (a) Latency; (b) Energy Consumption

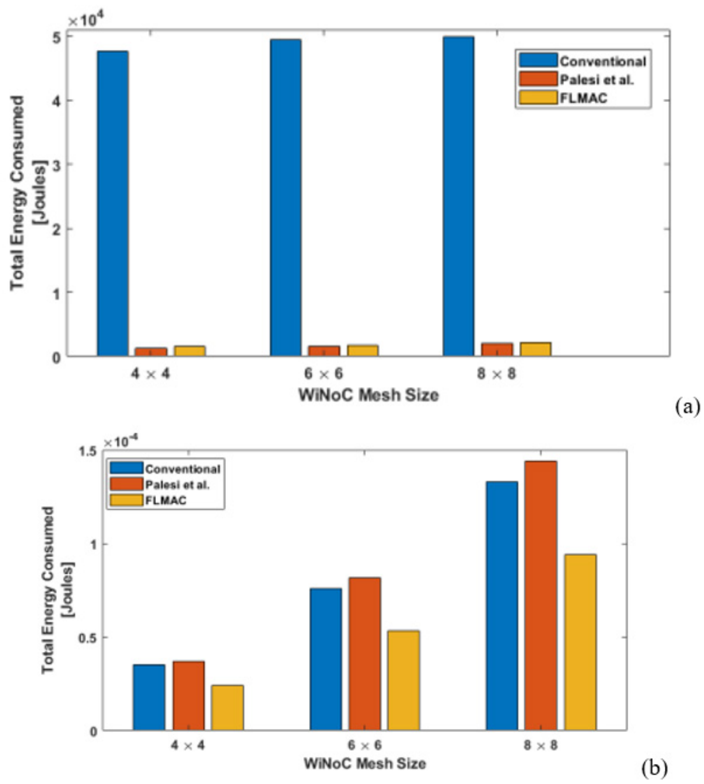


Figure 9: High Traffic Rate, λ = 0:05: (a) Latency; (b) Energy Consumption

low traffic FLMAC uses lesser energy. However, as the packet injection rate increases, the energy consumption of FLMAC increases accordingly. On the other hand, the conventional technique and Palesi *et al.,* (2015), do not take advantage of the low traffic rate, and the energy consumption remains constant even if the traffic rate is low. This performance gain is achieved by FLMAC while maintaining low latency, as shown in Figure 10(b). Figure 10(b) shows that FLMAC, on average, maintains the same latency as Palesi *et al.,* (2015).

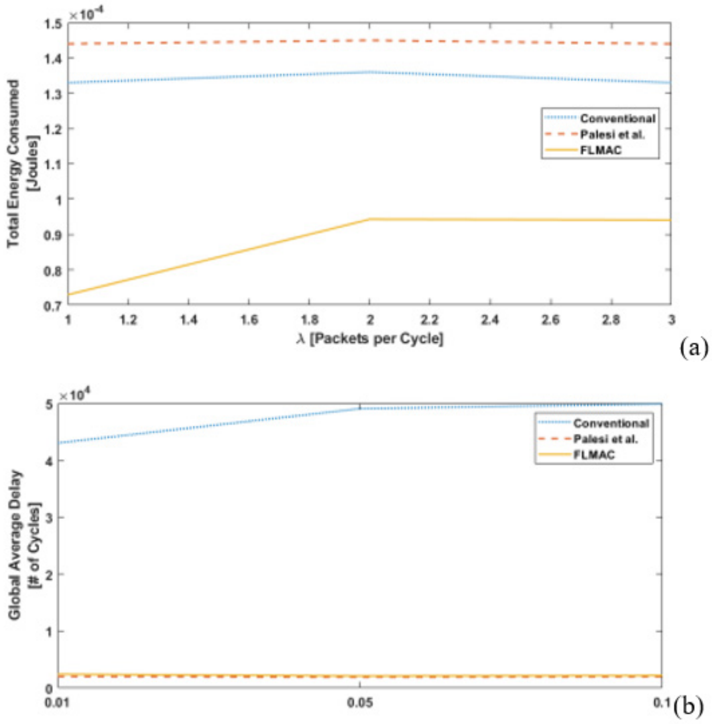


Figure 10: Effect of Traffic Rate, WiNoC Mesh Size = 8 × 8: (a) Energy Consumption vs Traffic Rate; (b) Latency vs. Traffic Rate

The efficient performance of FLMAC is due to adaptive control of data transmission rate by the proposed fuzzy logic controller. Thus, FLMAC can exploit the burstiness in the traffic, typical of data networks, by adaptively changing the transmission rate accordingly. It is worth noting that the computational energy is normally magnitudes lower than radio energy. Therefore, working on this observation, FLMAC can significantly lower energy consumption and energy dissipation.

Moreover, evaluating the performance of the FLMAC mechanism in WiNoC with most of the existing MAC mechanisms. We conducted a series of experiments using the same simulated setting in Table 2. We compared the performance of the FLMAC mechanism with two traditional MAC mechanisms, the Time Division Multiple Access (TDMA) (Matolak *et al.,* 2012), and Carrier Sense Multiple Access (CSMA) (Garcia-Luna-Aceves, 2017), also with RACM by Palesi et.al., (2015). The experiments aimed to compare the channel utilization, throughput, packet delivery ratio, and energy consumption of the FLMAC mechanism with the aforementioned MAC mechanisms. The four-parameter selected were explained in details as following:

1. Channel utilization: This metric measures the efficiency of channel usage in the WiNoC. Higher channel utilization indicates better resource allocation.
2. Throughput: Throughput measures the amount of data successfully transmitted within a given time period. Higher throughput signifies improved network performance.
3. Packet delivery ratio: This metric indicates the percentage of successfully delivered packets. A higher packet delivery ratio indicates better reliability.
4. Energy consumption: Energy consumption quantifies the amount of energy consumed by the WiNoC system. Lower energy consumption is desirable for energy-efficient systems.

The experimental results presented in the Table 3, shown that the proposed Fuzzy Logic MAC mechanism outperforms the other MAC mechanisms in terms of channel utilization, throughput, packet delivery ratio, and energy consumption. The FLMAC mechanism achieves higher channel utilization (88.5%) compared to RACM (83.4%), TDMA (75.2%) and CSMA (63.8%). It also demonstrates improved throughput (1.2 Gbps) and packet delivery ratio (95%) compared to the other MAC mechanisms. Additionally, the Fuzzy Logic MAC mechanism exhibits lower energy consumption (250 mW) compared to RACM (284mW), TDMA (310 mW)

Table 3: Comparative Performance Evaluation of the FLMAC-WiNoC Mechanism with RACM, TDMA and CSMA.

Performance Metric	FLMAC	RACM	TDMA	CSMA
Channel Utilization	88.5%	83.4%	75.2%	63.8%
Throughput	1.2 Gbps	985 Mbps	870 Mbps	780 Mbps
Packet Delivery Ratio	95%	91%	86%	78%
Energy Consumption	250 mW	284 mW	310 mW	380 mW

and CSMA (380 mW).

CONCLUSION

In conclusion, implementation of the Fuzzy Logic MAC mechanism in WiNoC demonstrates significant benefits in terms of enhancing system efficiency and performance. Taking advantage of the bursty nature of data traffic, this paper proposed a FLMAC mechanism that dynamically adjusts the data transmission rate based on the traffic load or packet arrival rate. The fuzzy logic controller efficiently adapts the transmission rate to reduce latency while also minimizing energy consumption. Cycle-accurate noxim simulation were used for the experiment to assess the performance of the purposed FLMAC. The results showed that FLMAC could effectively reduce energy consumption by adaptive data transmission rate control. In the experiment, FLMAC consumed lesser energy compared to existing techniques. The experimental evaluation results also show that the FLMAC mechanism outperforms traditional MAC mechanisms (TDMA and CSMA), even with RACM used to compare it. This highlights the potential of the FLMAC-WiNoC mechanism to effectively manage wireless channel resources in WiNoC architectures. Future research can focus on optimizing the fuzzy rule base and membership functions, considering additional system parameters, and evaluating the FLMAC mechanism on real-world WiNoC platforms. With continued advancements in wireless communication within multi-core SoCs, the adoption of the FLMAC mechanism holds potential promise for optimizing system performance and efficiency in WiNoC architectures

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