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# CONGESTION-AWARENESS ROUTING ALGORITHM FOR WINOC

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## *ABSTRACT*

Wireless network-on-chip (WiNoC) is the backbone for wired network-on-chip, which reduces the network diame- ter, energy consumption and enables high throughput. WiNoC reduces latency between distant nodes due to its ability to communicate wirelessly to a long-distance node with a single hop. However, as the demand for mutual wireless link increases, WiNoC radio-hubs become congested. This problem increases the average network latency as well as energy consumption rate. Hence, a suitable dynamic and efficient medium access control (MAC) mechanism is required to enhance wireless routers utilization. This study proposes a Centralized-MAC (C-MAC) mechanism that detects radio-hub (RHs) with the highest packet sizes in each cycle and allocates tokens based on RHi with the highest packet sizes. This proposed method significantly improves network throughput, latency, and energy consumption of the WiNoC compare with the existing methods. The simulation experiments show that the proposed C-MAC compared with the conventional round-robin (RR-based) and radio access control mechanism (RACM), has better performance in terms of average latency, throughput, and energy.

***INDEX TERMS*****:** C-MAC, Token-passing, WiNoC, Wireless inter- connect.

## I. INTRODUCTION

The modern systems-on-chip (SoCs) contain hundreds of cores, and as technology advances, the number of communi- cating elements increases. Maximizing SoC's benefits requires an efficient, scalable, and reliable communication infrastruc- ture [1], [2]. Network-on-chip (NoC) is considered the most viable communication infrastructure for resolving challenges encounter in SoC, dealing with the performance, energy, and reliability issues of many-core system architectures [3]. How- ever, as the wired NoC links become longer, the transmission suffers from long propagation delays, and higher energy usage, hence significantly degrade the overall network performance of NoC [4], [5]. The performance limitation in traditional NoCs arises from planar metal interconnect-based multi-hop communications. The data transfer between two distant cores causes high latency and power consumption, and this problem can be resolved using a wireless network-on-chip (WiNoC) [6], [7].

The emerging WiNoC architecture improves system band- width, enhances a high-throughput, reduces latency in data communications, low power consumption and deals with the scalability issues characterized in the next generation of many- core architectures cores [8], [9]. WiNoC is a wireless backbone placed on top of the traditional wired-based NoC, demonstrating high scalability [10], [11]. It is the combination of NoC with on-chip miniature wireless antennas that operate in the mm-wave bands [5], enhancing the communication with faraway cores by replaces the long-distance multi-hop communication paths in conventional wired-based NoC with a single-hop wireless links [12], [13]. Nevertheless, to explore the entire benefit of the emerging WiNoC architecture, there is a need for a control algorithm, fair and efficient medium access control (MAC) mechanism to enhance access of the on-chip wireless communication channel [6], [14].

The medium access control (MAC) mechanism is a network data transfer policy that coordinates the radio-hub communica- tion in WiNoC. An appropriate wireless MAC mechanism is required to ensure that the WiNoC resource can be utilized effectively [15]. The MAC mechanism needs to be simple and efficient, though many WiNoC architectures employ a simple token-passing MAC mechanism [16], [17], in which the Radio Hubs (RHs) are organized in a virtual ring (round- robin arbiter), and the token circulates among the WRs. Token is a specific small data flit generated by the wireless nodes [5], [17]. When a particular wireless node owns the token, it can use the wireless interface (WI) and transfer packets within a fixed duration of time. The advantage of this approach is that, it is simple and fairly distributed. With an increase in the numbers of RHs in WiNoC, it will require a longer time to complete the circulation.The limitation of this method is that the token can be allocated to RH that has no packet to transmit or has the least packet in the round because the design is a ring architecture, resulting in low latency and energy wasting. To ensure full utilization of wireless resources, maximum packet sizes in each round should be put into consideration. In actualizing this ideal, a suitable centralized MAC mechanism was designed, so that RH with the highest packet will be considered in each round.

This paper proposes a Centralized MAC (C-MAC) for WiNoC architectures, that would improve communication ef- ficiency and energy without losing the advantages of the low wiring overhead of the ring architecture. The main contribution of this paper includes the following;

1. We proposed a new arbitration technique that can main-tain good fairness among the wireless interfaces
2. The C-MAC mechanism allocates tokens according to the packet size in the wireless router, which assigns the wireless medium's right to use the wireless medium based on the radio hub with the highest packet size in each cycle.
3. The proposed centralized-MAC algorithm technique that will reduce token waiting time by enabling WIs with the highest packet to transmit.
4. The performance 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 2 reviews the related works. Section 3 is the proposed Centralized- MAC mechanism and the C-MAC design module. Section 4 is the experimental setup along with results and analysis. Finally, a brief conclusion of the paper in section 5 with recommendations for future work.

## II. RELATED WORK

Wireless interconnection has emerged as an energy-efficient solution to overcome delay experience in wire-line conven- tional NoC. There have been significant works on access control in WiNoC, access control is the process of mediating every requests to resources and data maintained by a system and determine whether the request should be granted or not. To fully utilize the WiNoC technology's benefit, an efficient medium access control (MAC) is required to ensure easy access to the on-chip wireless communication channel in WiNoC. MAC mechanism is responsible for ensuring efficient wireless bandwidth utilization by managing wireless channels among the WIs. Hence, the design of an efficient, low- overhead, and fair MAC mechanism is considered one of the critical challenges for WiNoCs [18], [19]. Some recent works [13], [17], [20], [21] proposed the dynamic MAC mechanisms which are capable of dynamically and effectively adjust the transmission or time slots of each token based WIs on a prediction estimated by the demand of the Radio Hub (RH) (that are usually considered in daisy- chained ring topology). Mansoor et.al [1] proposed a dynamic MAC mechanism in which the predicted bandwidth demand of the WIs are used for time slot allocation. The token time was adjusted based on predicted bandwidth demand. Mansoor et al. [13] improved on their earlier work and designed a low complexity and accurate traffic tracking mechanism that predicts a WI traffic demand. They proposed two dynamic MAC mechanisms that can adjust the slot durations based on the predictions. Then token time was adjusted based on the predicted bandwidth demand and Proportional Integral Differential (PID) but the wireless token still circulated within the WIs in a round-robin format [22].

Moreover, in a dynamic priority arbiter based on lottery mechanism [23], the arbiter detects loads of input ports in every clock cycle and adjusts the priority of each input port dynamically, then authorizes one input port to transfer data based on the lottery mechanism. Another method proposed is dynamic Radio Access Control Mechanism (RACM) [2]. In the RACM, the unemployed clock cycles were redistributed among the radio hubs to those who have used the radio channel completely in previous timelines. Priority-based MAC mech- anisms with Central Control Unit (CCU) [29] ensure efficient utilization of WiNoCs based on the length of the transmitted data packets; the CCU calculates each WIs' priority then distributes the right to use the wireless medium. Rad et.al [24] proposed an arbitration mechanism for crossbar switch that can fairly allocate the port priorities based on the current traffic load and the wireless channel bandwidth, this work adjust the dynamic priority for each input of the WR based on the current network status and the data packet length.

There are different types of MAC developed in the literature to actualized its efficiency, such as simple and distributed MAC mechanisms ALOHA [25], carrier sense multiple access (CSMA) [17], [25], Token based Time Division Multiple Access (TDMA) [5], a token-passing based Time Division Multiple Access (T-MAC) [17], [26], Code Division Multiple Access (CDMA) [27] is based on MAC that implements parallel communication between 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. Therefore, to improve wireless channel access in WiNoC, a C-MAC mechanism is required to allocate the token based on packet sizes in each RHi. The MAC mechanism was designed to adjust the token in the WIs based on packet sizes of the RHs rather than following the round-robin techniques. There are many types of research from the literature, but none have considered adjusting the Token Flow Control (TFC) based on packet size.

## III. THE PROPOSED CENTRALIZED MAC (C-MAC) MECHANISM

The primary idea behind integrating a set of radio hubs into WiNoC technologies is to alleviate the multiple-hops encountered in the conventional wired-NoC with one-hop wireless transmission. An arbitration mechanism plays an important role in WR to reduce congestion and enhance router performance effectively. The round-robin (RR) algorithm is a well-known arbitration mechanism that can guarantee fair scheduling and sharing of tokens in a radio hub. In the RR arbitration strategy, all input ports have an equal chance to own token for communication [1], [28]–[30]. Although RR arbiter performs well under uniform traffic loads, it is not flexible for some customized applications and distribution traffic loads, especially when packet generated are varies.

In the conventional RR algorithm, all RHs have an equal chance to own the token. A specified maximum number of cycles or time would be assigned to the generic i-th radio hub to access the radio medium when it owns the token. A maximum hold cycle ($MHC_i$) is statically determined and remains the same, irrespective of the traffic conditions; either the i-th radio hub has packets to transmit or not. However, in practical situations, radio hubs that did not have a packet to transmit could hold the token for a specific allocated duration. Others that have packets to transmit but not yet its turn to own token would result in system poor performance. Such unbalanced utilization of token allocation can be seen as an opportunity for MAC performance improvement. The diagram in Fig.1 and Fig.2 shown the RR and C-MAC WiMesh architecture with 8-RHs and 64-cores respectively.

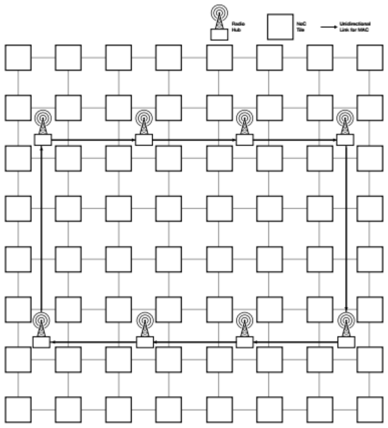


**Figure 1. Baseline RR WiMesh Architecture.**

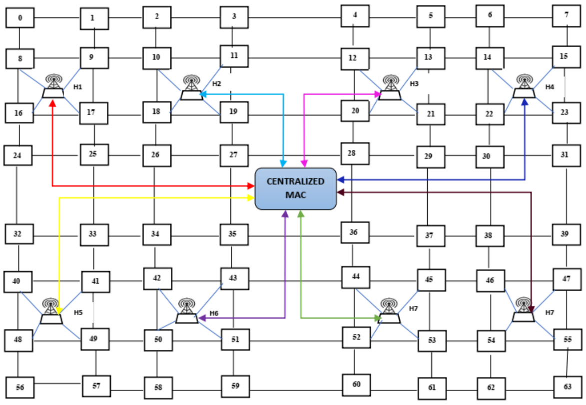


**Figure 2. C_MAC WiMesh Architecture.**

The proposed C-MAC basic idea is to allocate tokens to radio hubs (RHs) based on RHi packet sizes. More precisely, a suitable MAC mechanism ensures that wireless nodes use wireless media to communicate without any interference. In our design, C-MAC put into consideration the RHi with the highest packets in each cycle. Hence eliminates token allocation time-wasting and improves system performance. The pseudocode designed for implementing the proposed C- MAC is summarized by algorithm 1.

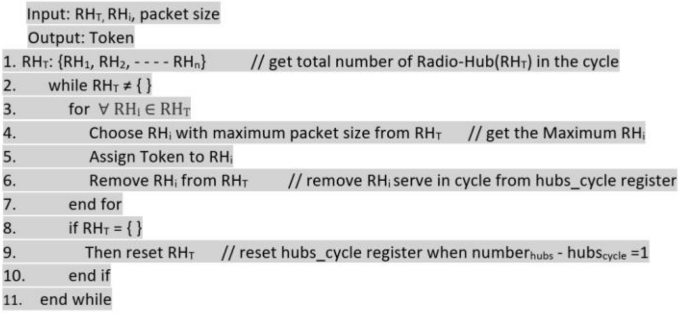
### *A. The design of the C-MAC module*

A centralized medium access control mechanism has been proposed based on the wireless interface packets' sizes. The C-MAC calculating unit was designed to select the radio hub with the highest packet size in the cycle and dynamically authorizes the wireless medium's user rights to use the token. In the C-MAC mechanism, the $RH_i$ with the highest packets would be allowed to transmit first, to ensure full utilization of wireless resources by taking the radio hub data packets sizes into account (Line 4 of the highest packet will be considered in each round.the algorithm 1). The basic router node in sub-network RHi needs to transmit the data packet to the transmission buffer (TB) the RHs. The C-MAC holds all the $RH_T$ packets in a hubs-cycle register where the maximum packet is selected (Line 1-3 of the algorithm 1). C-MAC dynamically allocate token to the wireless node having the highest packets. Figure 2 shows the C-MAC architecture of the proposed design for this research.

In the C-MAC module, the system calculates the total number of packets in each radio hub ($RH_i$), then updates the packets in the $RH_T$. The C-MAC contains a hubs-cycle register where all the $RH_T$ from RHi to RHn were stored at each cycle. The $RH_i$ with maximum packet sizes from $RH_i$ to $RH_n$ would receive tokens and use the MAC for a specific period of time. The hubs_cycle register in C-MAC will be updated every cycle. The $RH_T$ in the hubs-cycle register reduces every cycle and lessens the time taken to calculate the next maximum $RH_i$;

this will continue until equation 1 is valid. When hubs-cycle is empty, the hubs-cycle register in the C_MAC would reset and continue until no packet is updated again in the radio hub. the highest packet will be considered in each round.

$$numberhubs - hubscycle = 1 \quad (1)$$



```
Input: $RH_T$, $RH_i$, packet size
Output: Token
$RH_T$: {$RH_1$, $RH_2$, - - - - $RH_n$}        // get total number of Radio-Hub($RH_T$) in the cycle
    while $RH_T \neq \{ \}$
        for $\forall RH_i \in RH_T$
            Choose $RH_i$ with maximum packet size from $RH_T$     // get the Maximum $RH_i$
            Assign Token to $RH_i$
            Remove $RH_i$ from $RH_T$        // remove $RH_i$ serve in cycle from hubs_cycle register
        end for
        if $RH_T = \{ \}$
            Then reset $RH_T$     // reset hubs_cycle register when $number_{hubs}$ - $hubs_{cycle}$ =1
        end if
end while
```

**Algorithm 1: Proposed C-MAC Mechanism.**

## IV. EXPERIMENTAL RESULTS

### A. *Simulation Setup*

This section develops our WiNoC platform with a cycle- accurate network-on-chip simulation [29]; the noxim is a cycle-accurate NoC simulator that allows one to estimate system performance. We use 16-RHs deployed over the 8x8 conventional wired mesh-based architecture with a single radio channel. Also, we adopted a wormhole switching mechanism [31] in both wired and wireless links. In mesh architecture, we adopted dimension order XY-routing to provide a deadlock- free shortest path routing. The C-MAC is located in the center of the topology for authorizing RHs to use the wireless medium. The wireless NoC topology used for this research is shown in figure 2. The simulation runs for 100,000 clock cycles and with the first 1,000 warmup cycles. The simulations were repeated ten times, and the results were averaged to increasing the accuracy of the experimental results.

The simulation parameters used for this research are sum- marized in Table I, and the experimental results in section 4.2 compared our design with the conventional round-robin MAC and RACM mechanism. In terms of traffic distribution, we use the Random, Hotspot, Shuffle, and Transport traffic models for the synthetic traffic while the Fluidanimate, Blackscholes, Freqmine, and Swaption traffic models for application traffic to test the performance of the network.

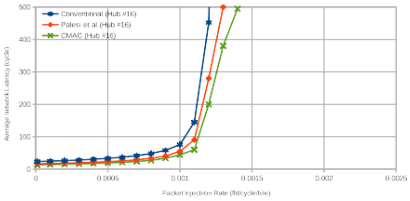
**Table I SIMULATION SETUP**

| PARAMETER | DESCRIPTION |
|---|---|
| Network Sizes | 8×8 (64 cores) |
| Number of Radio Hub | 4×4 |
| Synthetic Traffic Distribution | Hotspot, Random, Shuffle, and Transpose |
| Application Traffic Distribution | Fluidanimate, Blackscholes, Frequimie, and Swaption |
| Number of Channels | 1 |
| Simulation_Time Cycles | 100 000 |
| Technology | 65 nm |
| Clock Frequency | 1 Ghz |
| Switching Mechanism | Wormhole |
| Radio Access Control | Baseline Token Ring, RACM, Propose C-MAC |
| Selection Strategies | Random |
| Flit Size | 32 bits |
| Routing Algorithm | XY |
| Wireless Data Rate | 16Gbps |
| Wireless Communication | Millimeter-Wave |

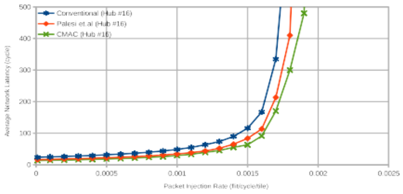
### B. *Results and Analysis*

In this section, we compare the proposed C-MAC mech- anism with the conventional RR and RACM mechanism. We implemented the proposed mechanism using the noxim simulator [29], which supports wireless communications. In this paper, network throughput, average network latency, and energy consumption were examined under four synthetic and application traffic patterns with different packet injection rates to obtain accurate results. The WiNoC simulator models the progress of the data flits accurately per clock cycle accounting for those flits that reach the destination and those stalled. We have considered a system size of 64 cores for this experiment as it represents the current trends in multicore chip design in the industry. Hundred thousand iterations were performed, and eliminating transients in the first thousand iterations.

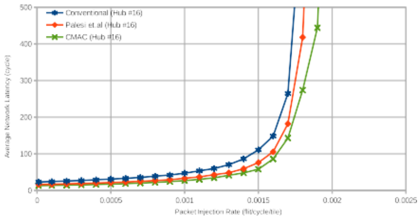
Fig. 3a–d and Fig. 4a-d are the synthetic and application traffic distributions of the average latency simulation results for an 8x8 mesh network-on-chip with 16-RHs; the average network latency is defined as the time required for a packet to traverse the network, from the time the head of the packet arrives at the input port to the time the tail of the packet departs the output port (received by the destination node). We observed from the simulation results that the C-MACs algorithm has a lower average delay for a given PIR value than the conventional RRs and RACM algorithm. This is mainly due to the proposed algorithm reducing the time taken to complete the radio hub circle by centrally controlling token allocation to each RHs and allocating token to RHi with the highest packet sizes in each cycle packets from sources to destinations in WiNoCs. Hence, the proposed mechanism in WiNoC has a better performance than RR MAC and RACM mechanism. The proposed mechanism shows more advantages on efficient decision-making over the RRs and RACMs mechanism. At low traffic load, the average latency of RR-based WiNoC would experience more delay in most of the RHs because some of the input ports have more packets than the other input ports. Therefore, the RHs with more packets suffer from a long delay in accessing the wireless interface channel.



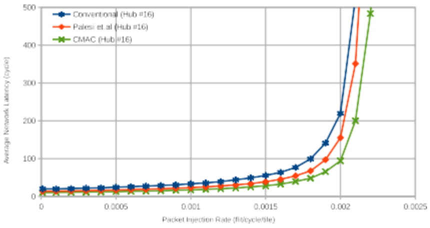
(a) Hotspot Traffic



(b) Random Traffic.



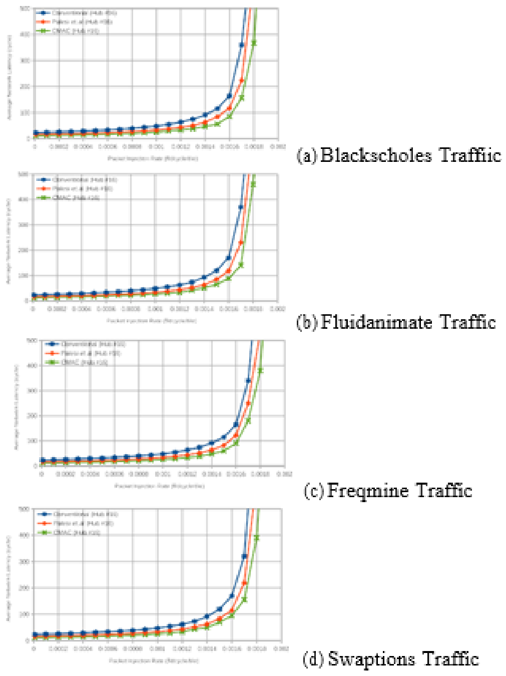
(c) Shuffle Traffic



(d) Transpose Traffic

**Figure 3. Average Latency of the 8x8-core with 16_WRs under Synthetic traffic patterns.**

The throughput of a network is the data rate in bits per second that the network accepts per input port. It the average rate of delivery of data over a communication channel or a node and is successfully delivered. Fig. 5a–d shows the network throughput of three arbitration mechanisms under four synthetic traffic patterns, while Fig. 6a–d showed the four application traffic patterns, respectively, as observed in these figures, while the packet injection rate gradually increases the network throughput increases. An increase in unsuccessful packet delivery will lead to lower throughput and degraded system performance. However, network throughput is being

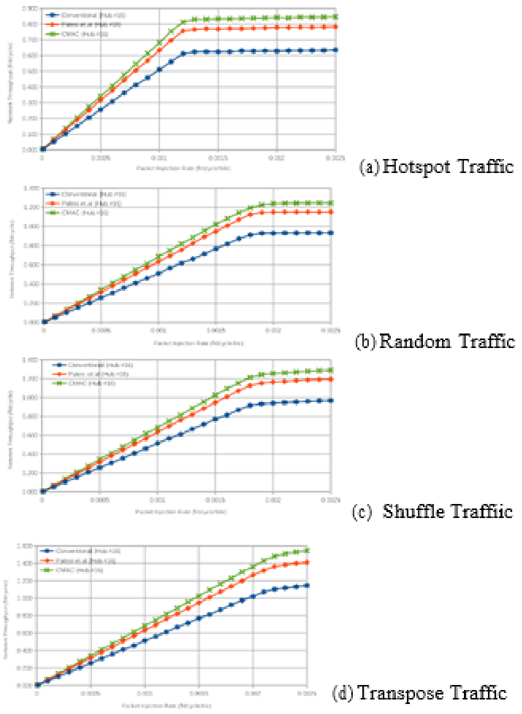


(a) Blackscholes Traffic

(b) Fluidanimate Traffic

(c) Freqmine Traffic

(d) Swaptions Traffic



(a) Hotspot Traffic

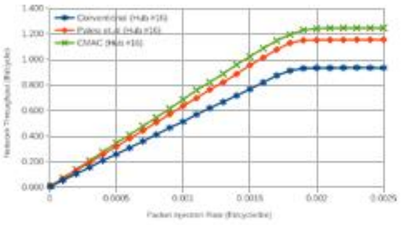
(b) Random Traffic

(c) Shuffle Traffic

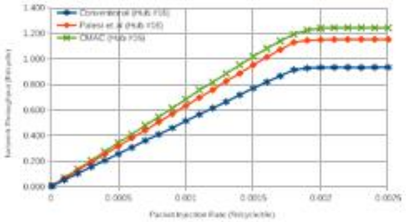
(d) Transpose Traffic

**Figure 4. Average Latency of the 8x8-core with 16_WRs under Application traffic patterns.**

**Figure 5. Network Throughput of the 8x8-core with 16_WRs under Synthetic traffic patterns**

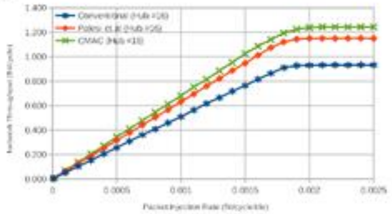


(a) Blackscholes

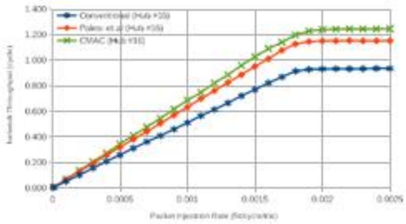


Traffic

(b) Fluidanimate Traffic



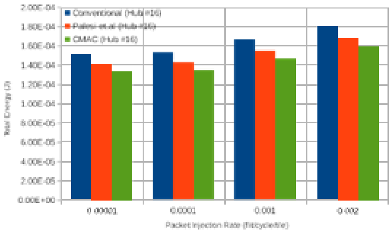
(c) Freqmine



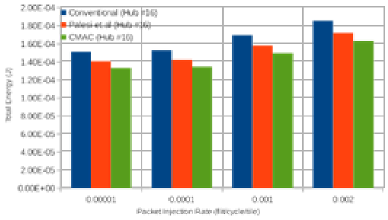
(d) Traffic

Swaptions Traffic

**Figure 6. Network Throughput of the 8x8-core with 16_WRs under Appli- cation traffic patterns.**



(a) Transpose Traffic



(b) Freqmine Traffic

**Figure 7. Energy Consumption of the 8x8-core with 16_WRs.**

Affected by different factors such as network congestion and packet loss. Hence the higher the throughput in the network reflect the more effective system. We compared the RR and RACM mechanism with the proposed C-MAC mechanism under different traffic scenarios, as shown in figures 7a-d and 8a-d. The proposed C-MAC showed better performance in the synthetic and application traffic patterns, at an average of 33% throughput compared to conventional RR and 8% compared to RACM.

Energy is defined as the average energy (i.e. both switch and link energy) required to successfully route an entire packet from source to destination. The simulation result of total en- ergy consumption for transpose synthetic traffic patterns, and freqmine application traffic patterns are shown in Fig. 7 a and b respectively. The energy consumption are modeled in noxim by a power configuration file. The RR and RACM consumed more energy than the C-MAC under different traffic patterns; the lower the energy consumption in any system design, the better the power characteristic in the system architecture. In the proposed mechanism, the network latency is reduced due to the allocation of the token to RHs based on the packet sizes of each RHi. In other words, the proposed mechanism leads to lower contention among the input ports of RHs, hence reduces the dynamic power consumption. The proposed method consumes lesser energy than RR and RACM due to the better utilization of wireless links and less contention of the input ports.

## V. CONCLUSIONS

In a WiNoC architecture, the routers augmented with a wireless interface; generally, RR-based was implemented us- ing a token-based mechanism. A token circulates through the radio hubs and enables the radio hub owning the token to use the radio medium for a certain number of clock cycles. The RACM dynamically tunes the hold time assigned to each radio hub by guarantee that the maximum token round time is below a given threshold. In this paper, we have presented a C-MAC mechanism that allows one to improve the utilization of the radio medium compared to the RR and RACM mechanism implemented in current WiNoCs proposed in the literature. The basic idea behind the proposed C-MAC is based on allocating tokens to RHi with the maximum packet sizes in the RHs. The proposed algorithm dynamically adjusts the RHs token allocation based on the packet sizes of each RHs in the cycle. The simulation results under synthetic and application traffic patterns show that the proposed arbitration mechanism reduces the average latency, improves the network throughput, and consumes lesser energy than the RR and RACM arbitration mechanism in WiNoC.

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