HoneyWiN: Novel Honeycomb-Based Wireless NoC Architecture in Many-Core Era

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Abstract. Although NoC-based systems with many cores are commercially available, their multi-hop nature has become a bottleneck on scaling performance and energy consumption parameters. Alternatively, hybrid wireless NoC provides a postern by exploiting single-hop express links for long-distance communications. Also, there is a common wisdom that grid-like mesh is the most stable topology in conventional designs. That is why almost all of the emerging architectures had been relying on this topology as well. In this paper, first we challenge the efficiency of the grid-like mesh in emerging systems. Then, we propose HoneyWiN, a hybrid reconfigurable wireless NoC architecture that relies on the honeycomb topology. The simulation results show that on average HoneyWiN saves 17% of energy consumption while increases the network throughput by 10% compared to its wireless mesh counterpart.

Keywords: MCSoC · Wireless NoC · Honeycomb · Mesh
Energy efficiency

1 Introduction

Even though the communication infrastructure has been gradually changed from traditional bus to Network-on-Chip (NoC) [1] during the last decade, the focus of Multi-Processor and Many-Core System-on-Chips (MP & MCSoCs) have been still on the 2-D metal wire interconnects [2]. Nowadays, NoC-based systems capable of accommodating hundreds of Processing Elements (PEs) are commercially available [3], but the multi-hop nature of these architectures has become a bottleneck on improving both performance and energy consumption parameters with technology scaling [4]. This motivates the researchers to seek alternative

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architectures such as Hybrid Wireless NoC (HWNoC) [5–7] in which the key idea is to adopt express communication links in order to reduce transmission latency with a reasonable energy consumption while providing high bandwidth.

1.1 Background

In order to transmit data across the chip in HWNoC-based architectures, different approaches have been introduced. The metal zigzag antennas [8] utilize Millimeter Wave (mm-Wave) as part of the ElectroMagnetic (EM) spectrum to operate in tens of GHz frequency. By employing mm-Wave approach in 40 nm CMOS technology, the data rate of 11 Gbps at 56 GHz frequency with Bit Error Rate (BER) of 10^{-11} has been reported [9]. By designing an On-Off Keying (OOK) transmitter in 65 nm CMOS, the data rate of 16 Gbps at 60 GHz frequency has been achieved [10].

In RF-I approach, EM waves travel via transmission line to exchange data between long-distance on-chip cores. One of the first implementation of RF-I has been proposed in 90 nm CMOS technology with the data rate of 5 Gbps [12]. Although the propagation can happen in light speed, RF-I suffers from crosstalk and scalability issues [2].

On the other hand, Carbon NanoTube (CNT) technology operates in terahertz/optical frequency range while reduces the size of antennas. In [19], a fundamental property analysis of the CNT antennas including input impedance, current distribution, and radiation pattern has been provided. Also in [7], a CNT-based on-chip network with 24 different frequency channels and data rate of 10 Gbps per channel has been utilized.

Moreover, graphene antennas also operate in terahertz frequency and provide low energy dissipation and less area overhead [20]. But these miniaturized antennas suffer from different challenges during implementation. For example, in nanoscale communication of the terahertz band, molecular absorption causes path loss and high noise [21]. Although a recent work to address this issue has proposed a channel model [22], more efforts are required to fully design and measure physical properties of the graphene antennas.

Surface Wave Interconnect (SWI) is another approach in which a 2-D waveguide medium is used as the wireless communication layer to propagate surface

Table 1. Wireless on-chip transceivers comparison

Category	RF-I				mm-Wave				CNT	SWI
Technology (nm)	65	90	90	130	40	65	65	90	N/A	65
Data Rate ($Gbps$)	5	5	8	25	11	16	23	10.7	10	25
Frequency (GHz)	60	20	N/A	N/A	56	60	80	60	100-10k	140
Energy (pJ/b)	1.33	1.2	1.05	1.67	6.4	1.2	9.4	6.24	0.33	0.32
BER	$< 10^{-12}$	N/A	$< 10^{-12}$	$< 10^{-12}$	$< 10^{-11}$	10^{-15}	10^{-11}	10^{-12}	N/A	$< 10^{-14}$
Modulation	ASK	BPSK	N/A	N/A	ASK	OOK	ASK	OOK	OOK	ASK
Trans. Range (mm)	5.5	N/A	5	20	14	20	20	100	23	20
Area (mm^2)	TX:0.0048	0.0107	0.002	TX:0.023	TX:0.06	TX: 0.077	TX:0.34	TX:0.15	N/A	0.408
	RX:0.034			RX:0.025	RX:0.07		RX:2.5	RX:0.29		
Reference	[11]	[12]	[13]	[14]	[9]	[10]	[15]	[16]	[7]	[17,18]

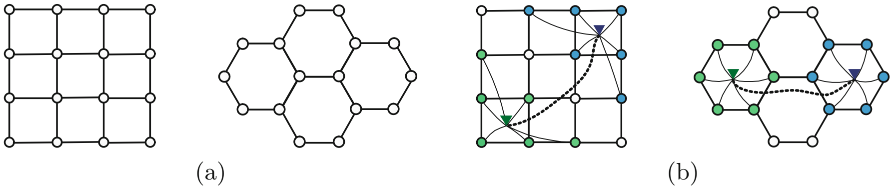

Fig. 1. Grid-like mesh and honeycomb topologies for 16-core system (a) Conventional (b) HWNoC

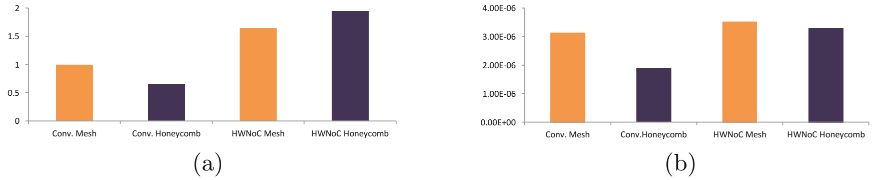

Fig. 2. Grid-like mesh and honeycomb topologies for 16-core system (a) Normalized network throughput (b) Total energy consumption (J)

wave signals. To physically implement this medium, a dielectric coated metal layer is used. Comparing with free space signal propagation environment, energy dissipation can be reduced substantially in SWI because of the signal propagation in 2-D communication fabric. The SWI-based architecture offers BER of less than 10^{-14} which is similar to BER of wired communication [17].

The comparison between different wireless on-chip transceivers are summarized in Table 1. The above efforts show how promising HWNoC is to be employed as the backbone of future MCSoCs. However, since Wireless Routers (WRs) are more energy hungry than Conventional Routers (CRs), new proposals are required to address the trade-off between energy and performance.

1.2 Motivation

There is a common wisdom that conventional grid-like mesh systems have better performance and reasonable energy consumption in comparison with other 2-D topologies. That is why almost all of the emerging HWNoC-based architectures also have been focused on grid-like mesh [23–26]. We run two sets of experiments to evaluate the correctness of this belief in conventional NoC and HWNoC.

Figure 1a shows a 16-core conventional grid-like mesh and a 16-core conventional honeycomb and Fig. 1b shows their hybrid wireless versions each equipped with two WRs. Figure 2a depicts the normalized throughput under Transpose1 traffic pattern for the mentioned topologies. Although the results confirm the superiority of the grid-like mesh over the honeycomb in conventional design, they show that this may not be the case for HWNoC-based systems. Moreover, the energy consumption comparison results in Fig. 2b reveal that although HWNoC-based architectures are by nature more energy hungry than conventional designs, the honeycomb topology can have less energy consumption compared to the well-known grid-like mesh.

These preliminary results not only challenge the efficiency of the mesh-based HWNoC, but also motivate us to seek alternative topologies in emerging MCSoCs. The contributions of this paper are as follows:

- Challenging the efficiency of the grid-like mesh topology in HWNoC-based architectures;
- Proposing an alternative Honeycomb-based Wireless NoC (HoneyWiN) architecture;
- Investigating the role of reconfigurable partitions (i.e. homogeneous/heterogeneous and complete/partial partitionings) in HoneyWiN;
- Introducing a specific routing algorithm for HoneyWiN by utilizing a planar 3-axes coordinate system.

To the best of our knowledge, this paper is the first to study the possibility of using honeycomb topology in HWNoC-based MCSoCs.

2 HoneyWiN Architecture

HoneyWiN consists of a wired network in which each 5-port CR is connected to its corresponding core and at most three adjacent CRs via wireline communication. Also another port is forecasted for a possible connection to a WR. On top of the wired network, a wireless network is adopted by WRs. Each WR is a multi-port router equipped with a transceiver that is capable of both wired and wireless communications.

2.1 Partitioning

Different partitions may lead to different trade-offs in terms of performance, energy consumption, and even area overhead. Here, on-chip partitioning can be viewed and examined from different viewpoints. One way to see partitioning is based on the number of cores within each subnet that can be homogeneous (i.e. all the subnets have equal number of cores) or heterogeneous (i.e. each subnet can have different number of cores from the others.) Homogeneous partitioning is suitable for the networks with uniformly distributed communications. On the other hand, heterogeneous partitioning can be used in the networks with high communication demand for some specific cores.

Another way to see partitioning is based on the participant cores in the process of subdividing that can be complete (i.e. all the cores participate in partitioning) or partial (i.e. some of the cores are involved in the process.) Complete partitioning can be utilized in the networks with high traffic rates while partial partitioning is beneficial for medium and low traffic rates.

Figure 3a is a 24-core partially homogeneous HoneyWiN with three WRs while Fig. 3b and 3c show two completely homogeneous partitionings by dividing the network into four and six partitions respectively. Figure 4a depicts a completely homogeneous partitioning of a 54-core HoneyWiN. In this example,

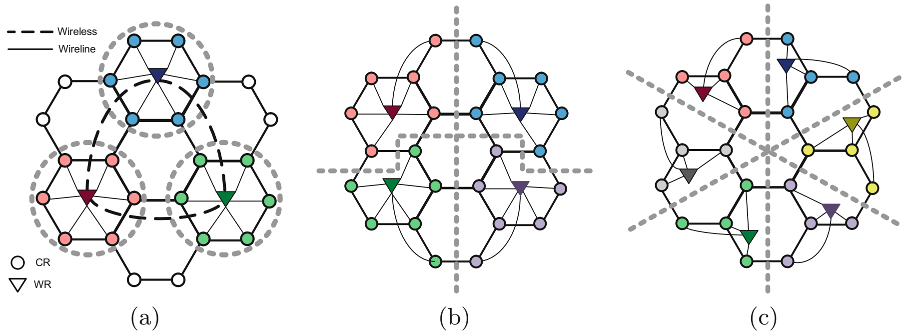

Fig. 3. 24-core HoneyWiN architecture (a) Partially homogeneous partitioning with three WRs (b) Completely homogeneous partitioning with four WRs (c) Completely homogeneous partitioning with six WRs

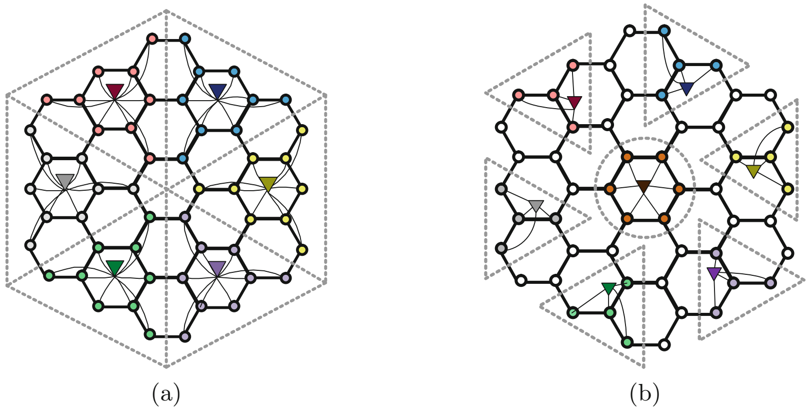

Fig. 4. 54-core HoneyWiN architecture (a) Completely homogeneous partitioning with six WRs (b) Partially heterogeneous partitioning with seven WRs

all the subnets are equipped with similar WRs. On the other hand, Fig. 4b illustrates a partially heterogeneous version of the same architecture. In this case, the middle subnet with more cores requires a stronger WR (i.e. a WR with more ports.)

Since in HoneyWiN, each CR has an additional port for wireless communication capabilities, multi-ports WR can be deployed to realize reconfigurable partitioning.

2.2 Routing

The proposed routing algorithm is based on a planar 3-axes coordinate system [27]. The X, Y and Z axes start from the center of the network and divide the topology into three regions. Packet traversal may happen via the wired network or the combination of wired and wireless networks. In each step, if the corresponding CRs of both source and destination cores are connected to two different WRs, express communication links are utilized to move the packet forward. In this case, long multi-hop wireline paths will be avoided. Otherwise, the algorithm adopts a turn model routing with wireline links [28]. In order to prevent deadlock in wired network, one out of six possible turns will be disabled in each clockwise and non-clockwise dependent cycles. Also, to prevent deadlock when packers are routed via both wired and wireless networks, in each input port of the routers two sets of Virtual Channels (VCs) are used [26]. One is for packet transmission from CR to WR while the other one is for packet transmission from WR/CR to CR. HoneyWiN routing algorithm is shown in Algorithm 1.

Algorithm 1. HoneyWiN routing algorithm

Input: Source router s and destination router d
Output: Routed packet
Initialization : n: Next router
WR: Set of wireless routers
$HC(a, b)$: Number of hops between routers a and b

```
while s ≠ d do
    ΔX = d.X − s.X ;
    ΔY = d.Y − s.Y ;
    ΔZ = d.Z − s.Z ;
    T = s.X + s.Y + s.Z ;
    if ∃i, j ∈ WR : HC(s, i) = 1 ∧ HC(d, j) = 1 ∧ i ≠ j then
        Route packet from s to i via wired link ;
        Route packet from i to j via wireless link(s) ;
        Route packet from j to d via wired link ;
        break ;
    else if ΔX < 0 then
        n = (s.X − 1, s.Y, s.Z) ;
    else if ΔZ > 0 then
        n = (s.X, s.Y, s.Z + 1) ;
    else if T = 1 ∧ ΔX > 0 then
        n = (s.X + 1, s.Y, s.Z) ;
    else if T = 1 ∧ ΔY > 0 then
        n = (s.X, s.Y + 1, s.Z) ;
    else if T = 1 ∧ ΔZ > 0 then
        n = (s.X, s.Y, s.Z + 1) ;
    else if T = 2 ∧ ΔX < 0 then
        n = (s.X − 1, s.Y, s.Z) ;
    else if T = 2 ∧ ΔY < 0 then
        n = (s.X, s.Y − 1, s.Z) ;
    else if T = 2 ∧ ΔZ < 0 then
        n = (s.X, s.Y, s.Z − 1) ;
    Route packet from s to n ;
    s = n ;
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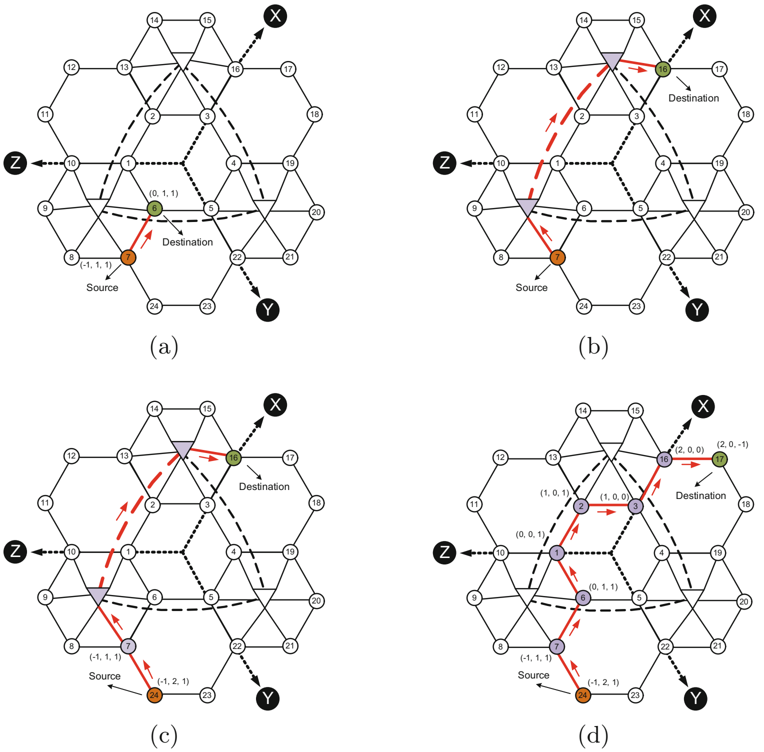


Fig. 5. Routing examples (a) 1-hop wireline (b) 3-hop wireline-wireless (c) 4-hop wireline-wireless (d) 7-hop wireline

Figure 5 shows different routing examples on the 24-core HoneyWiN architecture of Fig. 3a. As can be seen in Fig. 5a, the intra-partition communications will be done via wired links. On the other hand, for inter-partition communications, when the destination router is connected to a WR, the routing path will use both wired and wireless networks as shown in Figs. 5b and 5c. Otherwise, as depicted in Fig. 5d, only the wired network will be utilized. In other words, in order to prevent overutilization of WRs, only the packets in which their destination routers are connected to a WR are allowed to use the wireless network.

3 Experimental Results

For experiments, a SystemC-based cycle-accurate NoC simulator called Noxim [29] is used. Also, the energy analysis has been exploited by Orion 2.0 [30]. The comparisons are made between HoneyWiN and its mesh-based HWNoC counterpart for 24-core and 54-core networks. The simulation setup and traffics description are shown in Table 2.

Table 2. Simulation setup

(a) System configuration

Parameter	Value
Number of cores	24, 54
Number of WRs	2, 4, 6, 7, 8
Technology	65nm
Clock frequency	1 GHz
Switching mechanism	Wormhole
Radio access control	Token packet
Flit size	64 bits
Routing	XY, 3-axes
Wireless data rate	32 Gbps
Wireless communication	mm-Wave

(b) Traffic patterns

Pattern	Description
Uniform	Uniformly distributed traffic from source to destination
Transpose	Bit-permutation traffic using transpose matrix
Bit-reversal	Bit-permutation traffic from source to destination with reverse order address
Shuffle	Bit-permutation traffic from source to destination with shifted order address

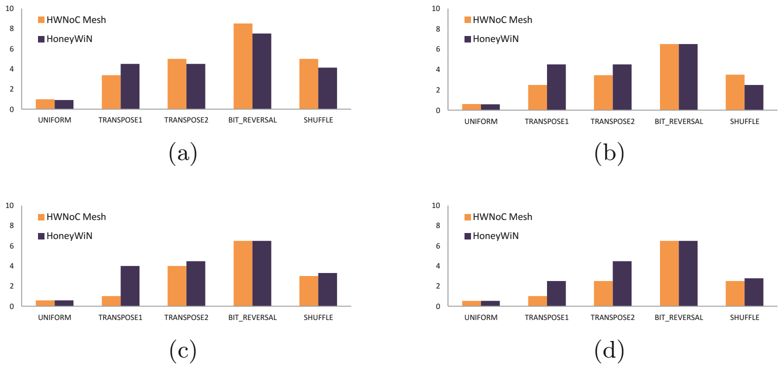


Fig. 6. Network throughput (flit/cycle) comparison for 24-core completely homogeneous system (a) Two WRs (b) Four WRs (c) Six WRs (d) Eight WRs

Network throughput comparisons for 24-core completely homogeneous system with two, four, six, and eight WRs with 0.1 injection rate are shown in Fig. 6. As can be seen, HoneyWiN has higher or equal network throughput in most of the benchmarks in comparison with mesh-based HWNoC.

In addition, Fig. 7 depicts the total energy consumption for the same architectures. As previously anticipated, HoneyWiN has less energy consumption than mesh-based HWNoC for all the benchmarks. Also according to Figs. 6 and 7, it seems that less number of WRs but stronger ones is more efficient in terms of both performance and energy consumption. However, the place and route stage for WRs with many ports is more challenging.

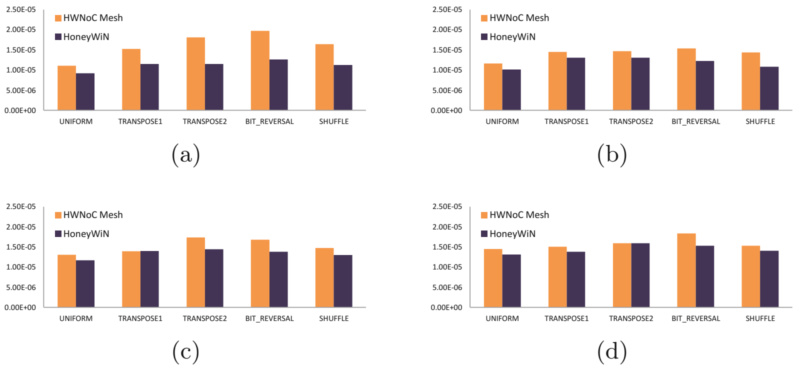


Fig. 7. Energy consumption (J) comparison for 24-core completely homogeneous system (a) Two WRs (b) Four WRs (c) Six WRs (d) Eight WRs

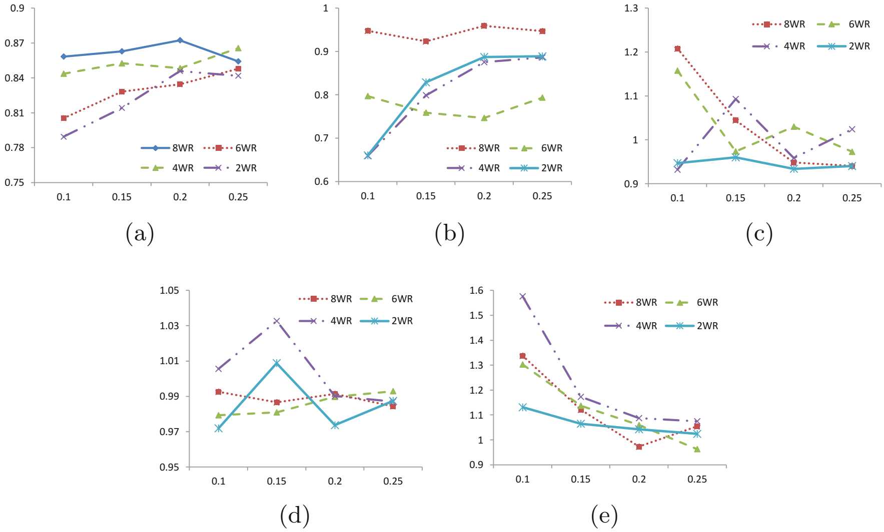
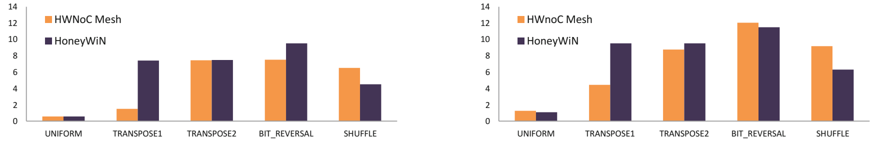


Fig. 8. Average delay ratio of HoneyWiN to mesh-based HWNoC for 24-core completely homogeneous system (a) Uniform (b) Transpose1 (c) Transpose2 (d) Bit-reversal (e) Shuffle

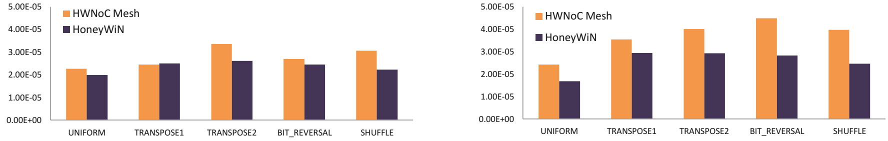
As another experiment, Fig. 8 shows the average delay ratio of HoneyWiN to mesh-based HWNoC by increasing injection rate. As can be seen, the delay ratio is less than one for most of the benchmarks. Also, generally HonwyWiN performs better than mesh-based HWNoC in high injection rates that makes this topology a suitable alternative for systems with frequent communications.

Moreover, throughput and energy consumption comparisons for 54-core completely homogeneous and partially heterogeneous systems are shown in Figs. 9 and 10 respectively. Although the average network throughput is almost the



(a) (b)

Fig. 9. Network throughput (flit/cycle) comparison for 54-core system (a) Completely homogeneous with six WRs (b) Partially heterogeneous with seven WRs



(a) (b)

Fig. 10. Energy consumption (J) comparison for 54-core system (a) Completely homogeneous with six WRs (b) Partially heterogeneous with seven WRs

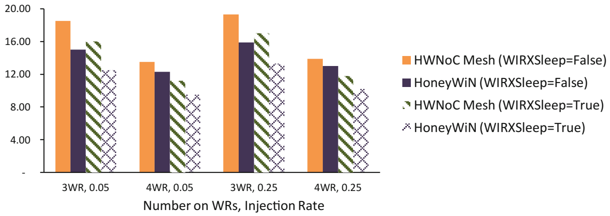


Fig. 11. Energy consumption (μJ) for 24-core system with/without power gating

same in both HoneyWiN and mesh-based HWNoC, more energy can be saved when HoneyWiN architecture is adopted. Besides, heterogeneous partitioning can provide more flexibility for application-specific architectures.

More energy can be saved by power-gating of WRs. In [31], a power gating method called WIRXSleep has been proposed to dynamically disable receiver modules and buffers of those WRs that will be not involved in any communication during the next forthcoming clock cycles. Figure 11 compares the energy saving for 24-core completely homogeneous systems with three (and four) WRs under 0.05 (and 0.25) injection rate for Transpose2 traffic pattern. As can be seen more energy can be saved when WIRXSleep is enabled.

4 Conclusion

In this paper, first we showed that mesh-based HWNoC does not always have the best performance and energy consumption in comparison with other 2-D topologies. Thus, it is a prejudice to assume that the grid-like mesh is the most stable network topology in emerging architectures. Then, we proposed a novel honeycomb-based HWNoC architecture called HoneyWiN along with its specific routing algorithm. The concepts of reconfigurable homogeneous/heterogeneous and complete/partial partitionings were also discussed. Finally, experimental results depicted that in comparison with mesh-based HWNoC, HoneyWiN saves more energy consumption (i.e. on average 17%) while still improves the network throughput (i.e. on average 10%). For future works, HoneyWiN-specific congestion-aware schemes [32] can be investigated.

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