J. Parallel Distrib. Comput. ■ (■■■■) ■■■–■■■

Contents lists available at ScienceDirect

J. Parallel Distrib. Comput.

journal homepage: www.elsevier.com/locate/jpdc

A novel hierarchical architecture for Wireless Network-on-Chip

Bahareh Bahrami [a], Mohammad Ali Jabraeil Jamali [b,*], Shahram Saeidi [c]

[a] Young Researchers and Elite Club, Khoy Branch, Islamic Azad University, Khoy, Iran
[b] Department of Computer Engineering, Shabestar Branch, Islamic Azad University, Shabestar, Iran
[c] Department of Computer Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran

HIGHLIGHTS

- For the placement of wireless hubs, two new methods are defined.
- Mesh and RCTM are considered as subnet topologies and their performance is studied.
- The AHP technique is used to select the appropriate structure for WNoC architecture.
- In the proposed WNoC architecture, the number of wired links and wireless hubs is minimal.

ARTICLE INFO

Article history:
Received 24 March 2017
Received in revised form 29 September 2017
Accepted 26 February 2018
Available online xxxx

Keywords:
Wireless Network-on-Chip
Hierarchical structure
Hub location
Topology
AHP

ABSTRACT

In the architecture of Networks-on-Chip (NoCs), wired structure and multi-hop communications can lead to high power consumption and latency. Wireless NoC (WiNoC) architecture is a new alternative to solve these challenges. In this architecture, long-range wireless links are used instead of multi-hop wired paths. In this paper, a combination of several topologies are investigated to develop an efficient hierarchical structure for the architecture of WiNoC. The performances of considered hierarchical structures are compared under different traffic patterns. Finally, by using the Analytic Hierarchy Process (AHP) technique, a new hierarchical wireless NoC is proposed. In the proposed architecture, hierarchical structure and wireless links with high bandwidth are regarded as two significant factors for reducing the number of hops between distant nodes. Based on the results of simulations, the proposed hierarchical structure has better efficiency than other WiNoC architectures.

1. Introduction

The need for fast data processing and the consequent increase in the number of cores on a chip have led to the development of the notion of Networks-on-Chip (NoCs) [7]. Although NoC has many advantages over bus architecture, it faces many challenges.

The increased latency and power consumption are regarded as two of the most important challenges attributed to the traditional architecture of NoC. With the increase in network size, distance between nodes increases. Hence, when a packet is transmitted between two nodes, which are located far from each other, passing via multi-hop routes will cause problems. According to the International Technology Roadmap for Semiconductors (ITRS) [23], the improvement of the features of metal links cannot properly account for the needs in this topic; hence, proposing new interconnections will be required. 3D [35], photonic NoC [39], and NoC with Radio Frequency (RF) interconnection [10] are some of the main approaches which have been proposed to solve the available challenges in NoC architecture. Although these approaches are capable of reducing latency and power consumption, they face challenges in design and manufacture [9,44].

The major features of Wireless Links (WLs) include a high bandwidth and the ability for telecommunications. A hierarchical structure along with WLs will allow moderating the challenges caused by the wired structure. Indeed, the WLs are used as shortcuts for the fast data transfer between distant nodes.

A hierarchical architecture for Wireless NoC (WiNoC) proposed by Ganguly et al. in which Carbon Nano Tube (CNT) antenna was used [20]. According to the studies conducted in [8,27], the emission and absorption in CNTs operating at optical frequencies indicate their antenna-like behavior; CNTs can be used as an on-chip antenna. The architecture proposed by Ganguly et al. was formed by dividing a network into subnets in which Processing Elements (PEs) are connected to each other. In each subnet, there is a central hub to which PEs are directly connected. Fig. 1 depicts the subnet structure of the architecture proposed in [20].

* Corresponding author.
E-mail addresses: L3_bahrami@yahoo.com (B. Bahrami), m_jamali@itrc.ac.ir (M.A. Jabraeil Jamali), sh_saeidi@iaut.ac.ir (Sh. Saeidi).

https://doi.org/10.1016/j.jpdc.2018.02.032
0743-7315/

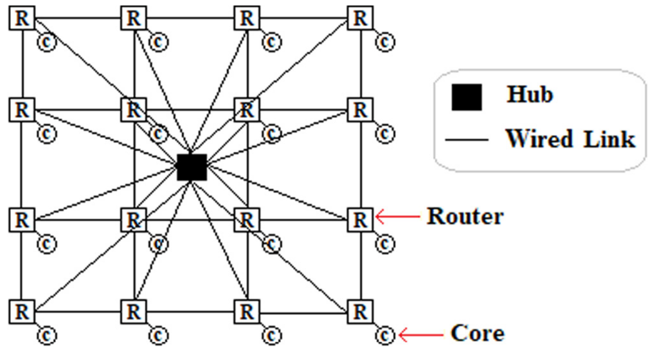

Fig. 1. Subnet structure [20].

As shown in this figure, using direct links reduces the number of hops. The bulk of traffic load passes via the hub. Hence, the central hub makes a traffic bottleneck [31]. Also, direct links between the central hub and routers increase the number of ports on the hub and routers. Assuming p as the number of ports on a router, the complexity of the crossbar will be equal to $O(p^2)$ [12,17].

In the second level of the hierarchy, hubs were connected to each other for wireless communication [15,20]. In fact, hubs are additional elements imposed on the system. The energy efficiency of wireless communications will be achievable when the path length is more than three hops [30]. Thus, the selection method of wireless hub location has become an important issue.

In this paper, a hub number-based approach and a method inspired by the n-queens problem were considered for the selection of wireless hub location. Because of the NP-hard nature of the n-queens problem [5,24], the Simulated Annealing (SA) method [29] and Genetic Algorithm (GA) [21] were also developed to solve the problem. The considered topologies for subnets include mesh and Ring-Connected Triangular Mesh (RCTM). The authors aimed to get a new efficient hierarchical architecture studied to combine the above-mentioned methods and topologies. For performance evaluation of the investigated structures, synthetic and real traffic patterns were used. The simulation results show that the performance of the proposed WiNoC architecture is highly desirable. The main contributions of this paper include the following:

- Four new hierarchical WiNoC architectures are studied.
- The Analytic Hierarchy Process (AHP) technique is used to select the appropriate structure for WiNoC architecture.
- In the proposed WiNoC architecture, the number of wired links and wireless hubs is minimal.

The remaining sections of the paper are organized as follows: in Section 2, related work is presented. The AHP is provided in Section 3. Section 4 describes the proposed structures for WiNoC architecture. The results of the simulation and the AHP technique are reported in Section 5. Conclusions and future work are given in Section 6.

2. Related work

Several methods including 3-D integration [35], optical interconnection [39], and wireless links [20] have been proposed to solve the problems related to the wired architecture in NoCs. Originally, the main goal of these methods is to reduce latency and power consumption. Because of the unique features of these methods, they can reduce latency and power consumption. However, these methods face challenges in the process of design and manufacture [9,44].

The notion of wireless interconnections was first used for the distribution of the clock signal [19,28]. In a WiNoC, the wireless links are used as shortcuts for the fast data transfer between distant nodes.

In [45], a Synchronous and Distributed Medium Access Control (SD-MAC) protocol using the Ultra Wide Band (UWB) technology is proposed for a WiNoC. Also, in [46], more research on UWB interconnections was provided. High data rate, low power consumption, and short-range communication are considered as the most important features of UWB interconnections.

In 2009, for on-chip wireless communications, a method in which a CNT antenna was used [33] was proposed. Different frequency channels can be allocated to the source and destination nodes; by using multiband laser sources in CNT antennas.

The notion of small world graphs [41] is used in some previous work [15,20]. In these works, the second level of the hierarchy is formed by a ring topology in which hubs are connected to each other. The authors used the SA method to find the location of wireless links so that only some of the selected hubs are equipped with wireless interfaces [16]. In this approach, since there is no limitation for selecting the type of subnet topology, different topologies can be used for the subnet [11,18,25,34]. With regard to the features of small world graphs, Deb et al. proposed a new hierarchical architecture for WiNoC in which mm-wave based antennas were used [15]. In all of these approaches [15,16,20,33], the available cores in each subnet should be directly connected to the hub which significantly increases the occupied area.

To meet the scalability demand, a hybrid architecture proposed by Karkar et al. in which the metal and Zenneck Surface Waves Interconnects (SWI) were used [26]. SWI provides broadcast/multicast capability.

Another approach in which WiNoC was formed by dividing a mesh network into subnets with the size of 5×5 was introduced by Wang et al. In this method, a baseline router located at the center of a subnet is replaced by a wireless router [22,42,43]. It is clear that the number of cores should certainly be a multiple of five. According to the findings from Wang et al., in [3,4,36], the authors have used optimization algorithms to reduce the number of routers.

Dai et al. have proposed a hybrid hierarchical WiNoC that uses an energy-proportional multicast scheme. Also, in this architecture, the efficiency of slotted p-persistent Carrier Sense Multiple Access (CSMA) protocol is studied [13]. Also, in [1], design aspects and challenges of broadcasting in the WiNoC have been studied.

In Tables 1, 2, and 3, some important previous approaches in recent years have been studied from various aspects. In Table 1, the Overlaid Mesh means a two-dimensional mesh topology so that the wireless nodes are located on it. Also, Overlaid Ring has the similar meaning.

3. Design methodology

Table 4 relates to the investigated hierarchical structures in this paper. To select the best structure, a well-known decision making method is the analytic hierarchy process.

The AHP is a structured technique to solve complex problems involving multiple criteria [37]. The principle of this technique is based on mathematics and psychology. The first step in the AHP is hierarchical structure development. The levels of this structure are the decision goal, the criteria, and the decision alternatives. Fig. 2 shows the AHP hierarchy for choosing the proper structure for WiNoC architecture.

After the construction of the hierarchy, a series of pairwise comparisons must be performed. Using pairwise comparisons, the relative importance of one criterion over another can be determined. A pairwise comparison matrix should be defined for each

Table 1
Summary of some previous architectures.

	Architecture	Protocol	First level topology (subnets)	Second level topology
Ganguly et al. [20]	Hierarchical	TDM & FDM	Star-Mesh	Overlaid Ring
Deb et al. [15]	Hierarchical	Token Passing	Star-Ring	Overlaid Mesh
Hu et al. [22]	Overlaid Mesh	SD-MAC	–	–
Rezaei et al. [36]	Overlaid Mesh	Token Passing	–	–
Bahrami et al. [4]	Overlaid Mesh	SD-MAC	–	–
Dai et al. [13]	Hierarchical	CSMA	Star	Fully connected
This work	Hierarchical	TDM & FDM	Mesh	Overlaid Ring Overlaid Mesh
			RCTM	Overlaid Ring Overlaid Mesh

Table 2
The features of the proposed structures.

	Total num. of PEs	Subnet size	# of routers in each subnet	# of hubs in each subnet	# of wireless routers
Ganguly et al. [20]	256	$4*4$	16	1	16
Deb et al. [15]	256	$4*4$	16	1	6
Hu et al. [22]	225	$5*5$	25	–	9
Rezaei et al. [36]	225	$5*5$	25	–	8
	256	$4*4$	16	–	8
Bahrami et al. [4]	225	$5*5$	25	–	4
	256	$4*4$	16	–	4
Dai et al. [13]	64	$2*2$	–	–	16
This work	256	$4*4$	16	1	4

Table 3
The main goal, advantages, and challenges of some previous work.

	Main goal	Advantages	Challenges
Ganguly et al. [20]	A highly efficient NoC	High bandwidth — Reduction of hop counts	Manufacturing issue & cost
Deb et al. [15]	An energy-efficient NoC	CMOS compatible — Reduction of hop counts	Limited frequency channels
Hu et al. [22]	An efficient NoC	Scalability — Reduction of hop counts	Board of antennas
Rezaei et al. [36]	An efficient NoC	CMOS compatible — Reduction of hop counts	Limited frequency channels
Bahrami et al. [4]	An efficient NoC	Reduction of area overhead	Application specific — Board of antennas
Dai et al. [13]	An energy-efficient NoC	Energy efficiency — Lower wired links — Capable to support multicasting	Large number of wireless router
This work	An efficient NoC	Reduction of area overhead — High bandwidth	Manufacturing issue

Table 4
Investigated structures.

Type	First level (subnets)	Second level (hubs)
1	Mesh	Ring
2	Ring-connected triangular mesh	Ring
3	Mesh	Mesh
4	Ring-connected triangular mesh	Mesh

criterion. Let A_i and A_j be alternatives. The relative importance of these alternatives is determined using Table 5.

For example, a value of 7 means that alternative A_i is 7 times more important than alternative A_j. The preference rating has psychological aspects and may vary from one person to another. Preparing a pairwise comparison matrix is the next step in the AHP. Suppose that $A_1, \ldots, A_n, (n \geq 2)$, be alternatives, a pairwise comparison matrix will be a $n \times n$ matrix so that element a_{ij} indicates the value of alternative i relative to alternative j. All elements of the main diagonal of the pairwise comparison matrix are equal to one. Also, the preference rating of a_{ji} can be obtained by computing the inverse of a_{ij}. In order to synthesize judgment following steps must be taken:

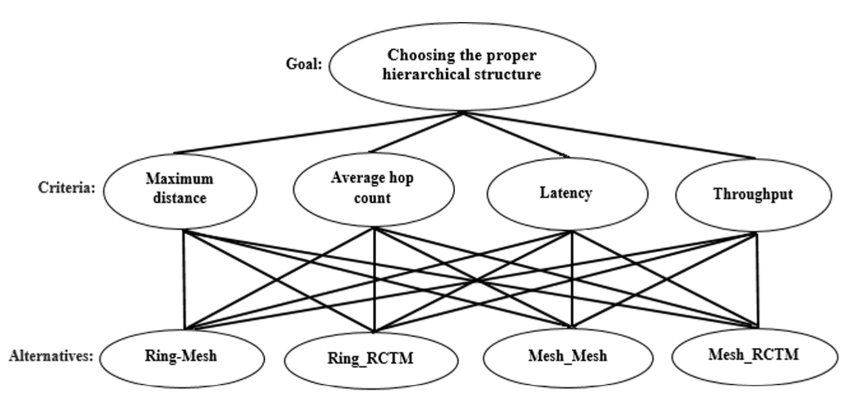

Fig. 2. The AHP hierarchy for choosing the proper structure for WiNoC architecture.

Please cite this article in press as: B. Bahrami, et al., A novel hierarchical architecture for Wireless Network-on-Chip, J. Parallel Distrib. Comput. (2018), https://doi.org/10.1016/j.jpdc.2018.02.032.

Step 0: Preparation of the pairwise comparison matrix based on the preference rating of the elements
Step 1: Total values of each column of the matrix must be calculated.
Step 2: Each element of the matrix must be divided by its column total.
Step 3: The average of the elements in each row of the normalized matrix must be calculated. These averages are calculated to provide an estimate of the relative priorities of the elements.

The above-mentioned process is performed for maximum distance.

• ***Step 0:***

Maximum distance	Ring_Mesh	Ring_RCTM	Mesh_Mesh	Mesh_RCTM
Ring_Mesh	1	1	1/3	1/3
Ring_RCTM	1	1	1/3	1/3
Mesh_Mesh	3	3	1	1
Mesh_RCTM	3	3	1	1

• ***Step 1:***

Maximum distance	Ring_Mesh	Ring_RCTM	Mesh_Mesh	Mesh_RCTM
Ring_Mesh	1	1	1/3	1/3
Ring_RCTM	1	1	1/3	1/3
Mesh_Mesh	3	3	1	1
Mesh_RCTM	3	3	1	1
Column totals	8	8	8/3	8/3

• ***Step 2:***

Maximum distance	Ring_Mesh	Ring_RCTM	Mesh_Mesh	Mesh_RCTM
Ring_Mesh	1/8	1/8	1/8	1/8
Ring_RCTM	1/8	1/8	1/8	1/8
Mesh_Mesh	3/8	3/8	3/8	3/8
Mesh_RCTM	3/8	3/8	3/8	3/8

• ***Step 3:***

Maximum distance	Ring_Mesh	Ring_RCTM	Mesh_Mesh	Mesh_RCTM	Priority vector
Ring_Mesh	0.125	0.125	0.125	0.125	0.125
Ring_RCTM	0.125	0.125	0.125	0.125	0.125
Mesh_Mesh	0.375	0.375	0.375	0.375	0.375
Mesh_RCTM	0.375	0.375	0.375	0.375	0.375
Total	1	1	1	1	1

To choose the best structure, the preference rating of other criteria depends on the traffic pattern. Hence, pairwise comparison matrices of other criteria are defined in Section 5.5. After calculating the weight of different alternatives for each criterion, pairwise comparisons of the criteria must be done. Finally, the proposed structures are prioritized using the priority vectors obtained from the alternatives and criteria.

4. Proposed architectures

In [2], single-hop and multi-hop WiNoC architectures have been studied. Based on the results, the single-hop architecture has a lower delay than the multi-hop architecture, and for some cases, there were no packet losses. Thus, single-hop WiNoCs can reduce some of the network challenges and increase parallelism. However, single-hop architecture has high power consumption. Also, it is mentioned that in the multi-hop architecture, transmitters, receivers, and signals can use less power. The purpose of this paper is to provide an efficient NoC architecture using wireless links. Hence, a hybrid hierarchical architecture using wired and wireless links is proposed. The idea is applicable by inserting the long-range wireless links in NoC architecture. The main advantages of using wireless links are their high bandwidth and low power consumption. A summary of the steps of defining a hierarchical WiNoC architecture is presented in Fig. 3.

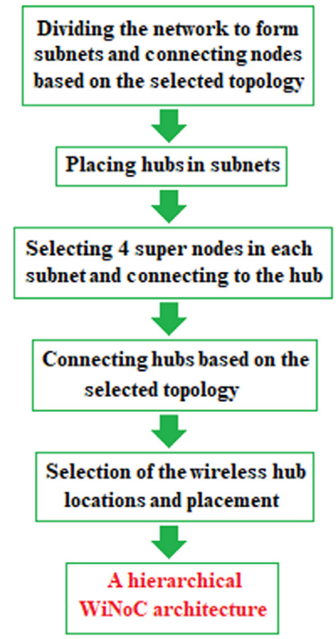

Fig. 3. Summary of the steps of defining a hierarchical WiNoC architecture.

At first, the subnets are formed by dividing the network into smaller parts of neighboring nodes. In each subnet, depending on the selected topology, the nodes are connected by the wires. Each subnet has a central hub. In terms of the structure, hubs and routers are similar to one another. But hubs have additional ports to communicate with the nodes inside the subnets instead of local ports. In each subnet, four nodes are selected and then these nodes are connected to the central hub via the wired links. By connecting the neighboring hubs, the second level of the hierarchy is formed. The hubs that are located far from each other communicate through the wireless links. These hubs are equipped with Wireless Base stations (WBs).

4.1. *The first level of the hierarchy*

In this work, a network with 256 nodes was studied. According to the findings in [20], the highest efficiency of the subnets is obtained in the 4 × 4 size. With regard to this issue, 16 subnets with 16 cores are considered in this paper. In each subnet, each router is connected to one core. Also, routers are connected to one another through wired links.

Inasmuch as the topologies of mesh and RCTM have similar features, they are considered as the subnet topologies in this paper. The investigated topologies for the subnets are illustrated in Fig. 4. Also, Table 6 gives a summary of the features of the two topologies, i.e. mesh and RCTM.

As shown in this table, these two topologies are identical in terms of the number of PEs, the number of wired links and the network diameter. Hence, their efficiencies can be compared with one another. It should be noted that the method proposed in [3] was used to calculate the average minimum hop count of the network ($H_{\min}$).

In case all the available nodes within a subnet are directly connected to the hub related to that subnet, 16 wired links will be required. Consequently, the area of the links will increase. To reduce the number of links, only four nodes are selected among all the available nodes within each subnet, so as to communicate with the related hub directly. Indeed, these four special nodes are regarded as super-nodes which can be directly connected to the

Table 5
The scale of relative importance [38].

Intensity of importance	Definition
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments

Table 6
Summary of the features of two topologies investigated for the subnets.

Topology	# of PEs	# of wired links	Max. Degree	Diameter	H_{min}
Mesh	16	24	4	6	2.5
RCTM	16	24	3	6	3

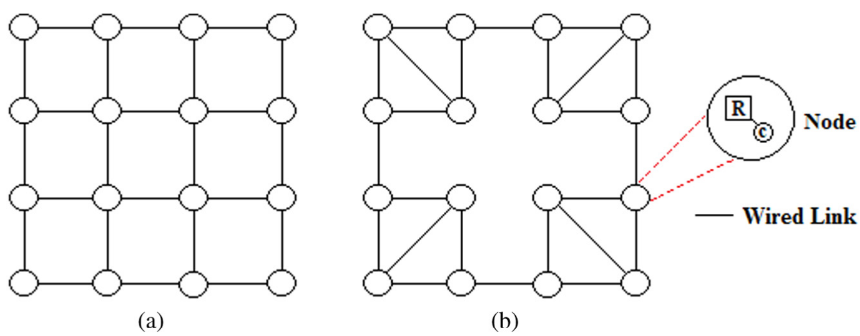

Fig. 4. The investigated topologies for the subnets: (a) Mesh (b) RCTM.

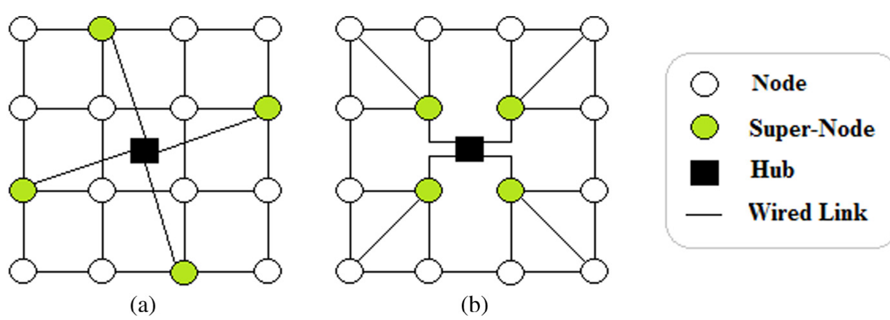

Fig. 5. Selection of super-nodes and the method of their connection to the central hub (a) Mesh (b) RCTM.

hub. In case each of the nodes wants to have access to the hub, they should first establish communication with one of the four selected nodes. It should be noted that super-nodes are selected in a way that the other nodes can get access to the hub within two hops. The selection of a few super-nodes or the inappropriate selection of the location of super-nodes can result in an increase in the number of hops of the network. Fig. 5 demonstrates the selection of super-nodes and the method of their connection to the hub.

Another issue which should be taken into consideration regarding the selection of super-nodes is the degree of a node. As depicted in Fig. 5, the maximum degree of nodes increases when the hub is connected to the super-nodes. However, this value has not gone beyond 4. Hence, common routers can be used in NoC. If super-nodes are selected in the way shown in Fig. 5, they can meet all the nodes in the network. Hence, it should be noted that the distance of each node from its related hub will be two hops and the distance of each super-node from its hub will be one hop. Fig. 6 illustrates the way in which nodes meet hubs in two different topologies.

Fig. 7 shows a schema of the communications among the PEs, super-nodes, and a hub.

If the source and destination of each data packet are in the same subnet, they can be transmitted through wired links and routers. Nevertheless, in case each of the three nodes located in the neighborhood of a super-node needs to transmit a packet to a node outside the subnet; they should access the hub through the super-node. Then, having passed through a number of hubs and routers, the packet reaches the destination. Each super-node has only one core and, regarding data transition and reception, it has only a one-hop distance to the hub. In this paper, it is assumed that each subnet has one hub, which is located at the center. It uses four wired links to communicate with the nodes. Furthermore, to prevent the contention and packet loss in this study, the above-mentioned links were only used for transmitting/receiving packets to/from other subnets. Hence, these links play no role in transmitting data between nodes within each subnet. With regard to the preceding discussions, a summary of the created changes in a subnet after the placement of a hub and wired links is given in Table 7.

4.2. The second level of the hierarchy

To establish a hierarchical network, the available hubs within subnets are connected to each other. Hence, the second level of the hierarchy is produced.

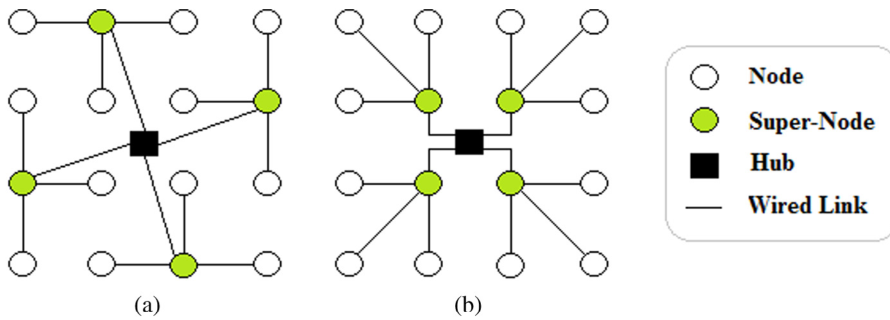

Fig. 6. The way nodes meet hubs in the topologies of (a) Mesh, (b) RCTM.

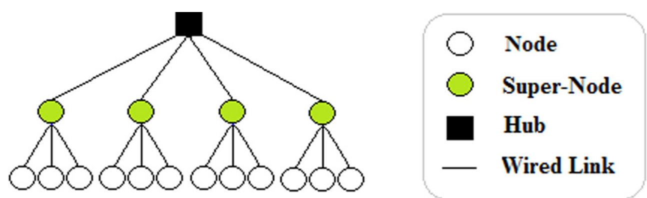

Fig. 7. A schema of the communications among processing elements, super-nodes, and a hub.

Table 7
Summary of creating changes in a subnet after the placement of hub and wired links.

Topology	# of wired links	# of Hubs	Max. Degree
Mesh	28	1	4
RCTM	28	1	4

4.2.1. Wireless hub location

Based on the studies conducted in [20], the highest efficiency of the subnets is accomplished in the 4×4 size. Thus, if it is assumed that there are N total available nodes in the network, the total number of hubs required for the network will be equal to ($K = N/16$). The simplest topology which can be considered for the wired connection of the hubs is the ring topology. In addition to its simplicity, the advantage of this topology is that it needs only a minimum number of links for communicating.

If all hubs are selected as wireless hubs, this issue will lead to a significant increase in the occupied area. Another disadvantage of this approach is the excessive power consumption. Thus, the number of wireless hubs and their location are important issues that must be considered.

4.2.1.1. Hub number-based selection method. To obtain the energy efficiency of wireless communications, the path length should be more than three hops [30]. Hence, it is assumed that $K/4$ of the total required hubs are wireless. In this paper, the hub number is used to select a hub that can be equipped with wireless interfaces. For this purpose, the hubs having the number divisible by four will be selected. Fig. 8 illustrates the selected locations for the placement of the wireless hubs based on the hub number.

However, the distance between the hubs might increase due to the selection of this number of wireless hubs. To prevent this problem, a fully-connected method was used to establish wireless communications among wireless hubs.

4.2.1.2. Inspired method of the n-queens problem. The major drawbacks of ring topology are a large occupied area, low path diversity between nodes, and low reliability. Hence, in this paper, mesh topology is also studied. The hub number-based selection method is simple, but the number of hubs should certainly be a multiple of four. Because of the similarity between a mesh topology and a chessboard, the n-queens problem can be used to select the location of the wireless hub in the mesh topology. It is assumed that in a mesh topology, hubs represent the chessboard squares and a wired link is defined between two hubs if two squares on a chessboard are adjacent.

In 1848, Max Bezzel introduced the eight queens puzzle. The first solution for this problem was published by Franz Nauck. Also, Nauck extended the problem to the n queens, with n queens on a $n \times n$ chessboard. The n-queens problem has many applications in various sciences. By placing n non-attacking queens on a $n \times n$ chessboard, according to the chessboard rules, one solution to this problem will be obtained. Fig. 9 shows the unacceptable locations for the placement of the next queen.

In Fig. 9, white cells are the acceptable locations for the placement of the next queen. For $n = 2$ and $n = 3$, this problem is not defined. If only one queen is placed in each row and each column, the search space will be equal to the permutation of n queens. In this paper, the simulated annealing method and genetic algorithm are used to solve the problem. These two algorithms can be used to solve a wide range of problems.

(a) The simulated annealing method

The simulated annealing method was proposed by Kirkpatrick et al., in 1983. In fact, SA method simulates the cooling of a material. In this process, one material is heated up to its melting point and then its temperature is gradually reduced. The temperature reduction process is so slow that the material is in the thermodynamic balance. The algorithm finds a new solution through the previous solution. Those changes which will improve the results are accepted. However, under some circumstances, it is probable that those changes which lead to worse results might be accepted. Of course, the probability of this event decreases as the temperature decreases.

To generate the initial solution, one solution is encoded in the permutation form: $[\pi(1), \pi(2), \pi(3), \ldots, \pi(n)]$. The value of $\pi(i)$ represents the row number and i indicates the column number of a queen on the chessboard. Through this method, there are no two queens on the same row or column. Thus, the search space is reduced to $n!$. An initial solution for SA method is generated by the random permutation of n queens in a string. For the n-queens problem, the value of cost function is calculated by counting the number of attacks. An optimal solution is formed from a permutation of n queens without any attacks among them.

Fig. 10 relates to the pseudo-code of SA method. In the pseudo-code, P means the number of attacks. In this paper, to create a neighborhood in SA, three methods of insertion, reversion, and swap were used. Also, three cooling schemes [32] were used which are

- *Geometric cooling scheme*: $T = \alpha \times T$; $(0 < \alpha < 1)$. *In this paper, it is assumed that alpha is equal to 0.95.*
- *Linear cooling scheme*: $T = T - \beta$; *β is a constant value.*

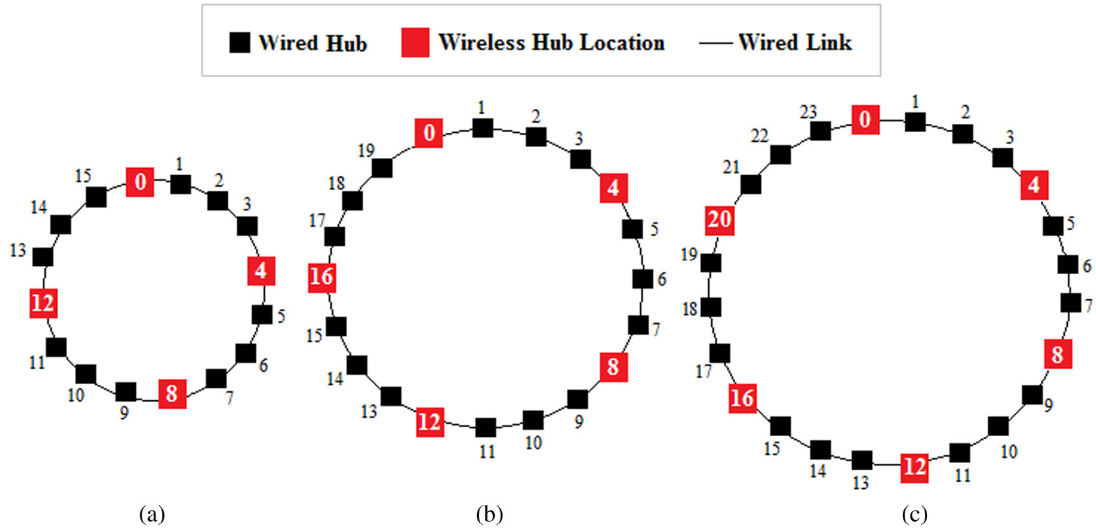

Fig. 8. Selected locations for the placement of the wireless hubs based on the hub number: (a) $k = 16$, (b) $k = 20$, (c) $k = 24$.

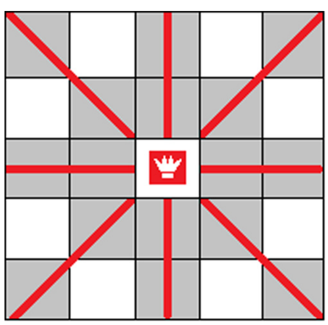

Fig. 9. Unacceptable locations for placement of the next queen.

- *Logarithmic cooling scheme*: $T_i = T0/log(1 + i)$, where T_i represents the temperature at iteration i.

(b) Genetic algorithm

The genetic algorithm is a population-based algorithm. This algorithm was proposed by Holland in the 1970s. The main operators of this algorithm are crossover and mutation. By applying these operators to the initial population, a new population is created. Fig. 11 shows the pseudo-code for the genetic algorithm.

In the second line of the GA pseudo-code, Create Random Solution refers to a function which is intended to produce random sequences that called chromosomes. For this purpose, a permutation function is used. As mentioned earlier, in the permutation form: $[\pi(1), \pi(2), \pi(3), \ldots, \pi(n)]$, the value of $\pi(i)$ represents the row number and i indicates the column number of a queen on the chessboard. The length of the chromosomes is equal to the number of queens. Then, in the third line of the algorithm, based on the initial solutions, the cost function is evaluated. In the next stage, according to the obtained costs, the members of the population are sorted. Furthermore, the best solution and its cost are stored. Also, in the Main Loop, crossover and mutation operators applied on the population members. In this paper, the single point crossover operator was used and the crossover rate was equal to 0.8. For applying the mutation operator, three methods of insertion, reversion, and swap were used. Mutation percentage was equal to 0.2 and mutation rate was 0.02. The best values for these parameters have been selected based on the try and error. In the next step, main population, offspring, and mutant population are merged to create a new population. After sorting the population according to the cost function, the new population is selected from these members and the rest will be removed. At this stage, the roulette wheel selection method was used. Finally, the best solution and the best cost will be stored.

For a given n, there are different solutions to the problem. Each of the optimal solutions obtained for the n-queens problem can be used for the placement of wireless hubs. However, by placing the wireless hubs on a particular part of the network, if a greedy routing algorithm such as Dijkstra is used, the risk of collision will increase. Because wired hubs will compete to use the shortcuts and a large part of the traffic will be transmitted to the wireless hubs. Thus, those fundamental obtained solutions are preferred that are fair for the distribution of wireless hubs. Fig. 12 illustrates the solution for the 4-queens problem.

In Table 8, based on the total number of hubs, the features of two selection methods for the placement of wireless hubs are

Pseudo Code of Simulated Annealing

Input Model:
T0=1000 % Temperature
Number of Queens
f: Cost function
Output: *The location of queens (Hubs)*

```
Set the initial temperature (T=T0)
Create initial solution (s0)
P = Calculate f (s0)
while ( P > 0 )
   Create Neighbor (s)
   Calculate f (s)
   if ( f (s) < P ) then
      s0 = s
      P = f (s)
   else
      Generate r: A uniform random number between 0 and 1
      if r < e^( f (s0) - f (s) ) / T then
         s0 = s
         P = f (s)
   Reduce temperature
Return s0
```

Fig. 10. The pseudo-code of simulated annealing.

Table 8
The features of two selection methods for the placement of wireless hubs.

Total number of hubs	Hub number-based method for the ring topology		n-queens based method for the mesh topology	
	# of wireless hubs (v)	# of wireless links	# of wireless hubs (v)	# of wireless links
16	$\frac{16}{4}=4$	$\frac{4\times3}{2}=6$	$\sqrt{16}=4$	$\frac{4\times3}{2}=6$
20	$\frac{20}{4}=5$	$\frac{5\times4}{2}=10$	Impossible	Impossible
24	$\frac{24}{4}=6$	$\frac{6\times5}{2}=15$	Impossible	Impossible
25	Impossible	Impossible	$\sqrt{25}=5$	$\frac{5\times4}{2}=10$
K	$\frac{k}{4}$	$\frac{k\times(k-4)}{32}$	$\sqrt{k}$	$\frac{k-\sqrt{k}}{2}$

```
Pseudo Code of Genetic Algorithm
Input Model:
n_pop: Population Size
MaxIt: Maximum Number of Iterations
n_c: Number of offspring (Parent)
n_m: Number of Mutants
Output: The location of queens (Hubs)

%% Initialization
for i = 1 to n_pop do
Initialize: Create Random Solution
Evaluation
end
Sort Population
Store Best Solution
Store Cost

%% Main Loop
for it = 1 to MaxIt do

  % Crossover
  for i = 1 to (n_c / 2) do
      Select Parents Indices
      Select Parents
      Apply Crossover
  end

  % Mutation
  for j = 1 to n_m do
      Select Parent
      Apply Mutation
      Evaluate Mutation
  end
  Create Merged Population
  Sort Population
  Update Worst Cost
  Truncation
  Store Best Solution Ever Found
  Store Best Cost Ever Found
end
```

Fig. 11. The pseudo-code of genetic algorithm.

presented. In the hub number-based method, the value of k (total number of hubs) must be a multiple of 4. Hence, for $k = 25$, it is impossible to define the number of wireless hubs and the number of wireless links. In the n-queens based method, like a chessboard, in both dimensions, the number of hubs should be the same. Thus, for $k = 20$ and $k = 24$, it is impossible to define the number of wireless hubs and the number of wireless links. In the hub number-based method, the total required wireless hubs is equal to $K/4$. This value for the n-queens based method is equal to: $\sqrt{k}$. Thus, it can be stated that in the inspired method of the n-queens problem, the required wireless hub number is smaller. In both selection methods, the fully-connected method is used to establish wireless communications between wireless hubs. In the fully-connected method, with v vertices (or wireless hubs), the number of edges (or wireless links) is equal to $\frac{v\times(v-1)}{2}$.

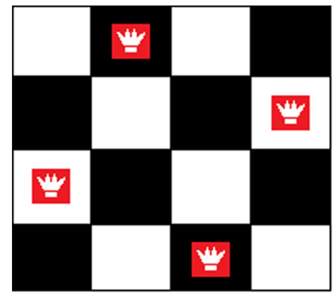

Fig. 12. The solution for the 4-queens problem.

The investigated structures are shown in Fig. 13. It should be noticed that all of the links were assumed to be of the bidirectional type.

Table 9 gives an outline of the features of the two proposed structures to communicate among hubs for 256 nodes.

4.3. Antenna

The hubs for which wireless links are defined should be equipped with WBs. The wireless port of a WB includes the following components: antennas, transceiver circuits, electro-optic modulator/demodulator, Low-Noise Amplifier (LNA), and TDM modulator/demodulator. The neighboring hubs are connected to each other through wired links for preventing the area overhead of wireless ports. In [20], the total area of wireless ports for a WiNoC with 6 wireless links was estimated to be 5343 μm^2. The wireless links are only used between hubs which are far from each other.

In this paper, the CNT antenna proposed and discussed in [20] is used for wireless communicating among hubs. These antennas have significant data rates. By using multiband laser sources in CNT antennas, different frequency channels can be allocated for the source and destination nodes. The Frequency Division Multiplexing (FDM) is used to allocate channels with a different frequency between nodes. According to the investigations conducted in [20], 24 continuous wave laser sources of different frequencies can be allocated for wireless links in WiNoC. By utilizing the Time Division Multiplexing (TDM) technique as well as FDM, the number of distinct channels can be increased. The detailed description of the antenna design is out of the scope of this paper.

4.4. The switching strategy and routing algorithm

In this study, the wormhole switching strategy is used according to which a data packet is divided into smaller sections known as flow-control units (flits). A head flit keeps the routing and control information. Indeed, path calculation is implemented on the head flit of a packet and the remaining flits related to that packet follow the head flit. Fig. 14 shows a packet format.

A packet consists of several fields. The most important of these fields are type, sequence number, virtual channel, a destination

Please cite this article in press as: B. Bahrami, et al., A novel hierarchical architecture for Wireless Network-on-Chip, J. Parallel Distrib. Comput. (2018), https://doi.org/10.1016/j.jpdc.2018.02.032.

Table 9
Outline of the features of two proposed structures to communicate among hubs for 256 nodes.

Topology	# of Hubs without WLs	# of Hubs with WLs	# of wired links	# of wireless links	Max. distance (hops)	H_{min}
Ring	12	4	16	6	5	2.34
Mesh	12	4	24	6	3	1.92

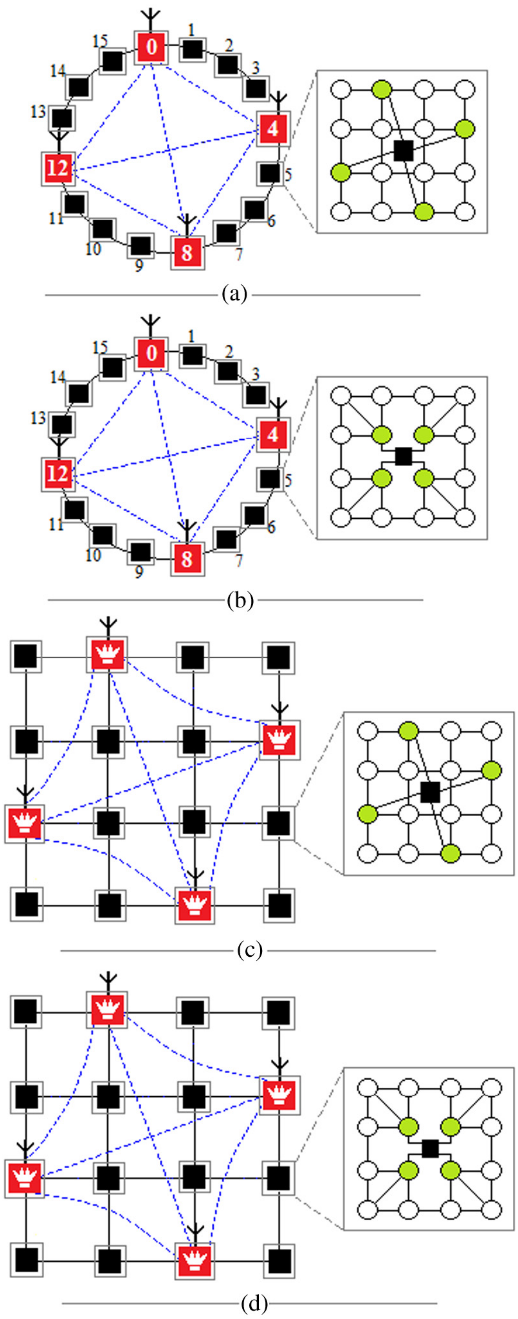

Fig. 13. Investigated structures: (a) Ring_Mesh, (b) Ring_RCTM, (c) Mesh_Mesh, and (d) Mesh_RCTM.

identifier, and a source identifier. In summary, the type field is used to define different categories of packets. Also, the sequence number field is used to support out-of-order delivery. The number of virtual channels is indicated by the VC field. Both of the destination identifier and the source identifier consist of subnet identifier and node identifier fields. Also, the node identifier field includes a super-node identifier and PE identifier. More details about the fields are out of scope in this paper.

Table 10
The processing elements coding method.

PE_id	Meaning
00	Local port
01	Right node
10	Left node
11	Front node

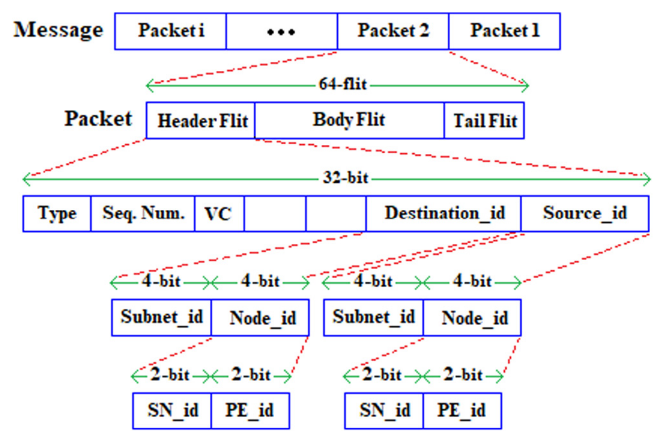

Fig. 14. A packet format.

For node numbering, there are 16 subnets. So, 4 bits is enough for subnet coding. Also, in each subnet, there are 16 nodes. The 4 nodes of these 16 nodes are super-nodes. For coding of intra-subnet nodes, 4 bits is enough, which are two bits for the super-nodes coding and two other bits for the processing elements coding. In this paper, the super-nodes coding is based on row-order. Table 10 is related to the processing elements coding method.

For the subnet numbering, both row numbers and column numbers are used. In Fig. 15, an example of the numbering method for nodes is given. The nodes of RCTM topology are numbered in the same way.

The routing method in the proposed architecture is based on using the shortest path between the sources and destinations. In this paper, Dijkstra's algorithm is used to avoid the complexity of the design. In this algorithm, the adjacency matrix of the network is used to calculate the shortest path. To calculate the shortest path, one node is considered as the start node and the paths starting from this node are calculated to all the nodes after scrolling. Route calculation is carried out on all the nodes only once at the beginning of the work. The selected paths are stored in all the hubs and routers. In Dijkstra's algorithm as a greedy algorithm, from a source to a destination, there is only one path and that is the shortest path. Therefore, if a failure occurs on the path, the data will not transfer. As a result, this greedy algorithm is not a fault-tolerant algorithm.

As discussed earlier in the paper, since using a hub and connected links to it through the super-nodes enhances the congestion probability in routing, the hub and its four links are not involved in intra-subnet routing. To reduce the overhead, routers in a subnet have no information of other subnets and just keep routing information of their subnet. Identifiers included in the packet are used to detect subnets. If the source and destination nodes are in a subnet, according to the routing table, the shortest path is selected

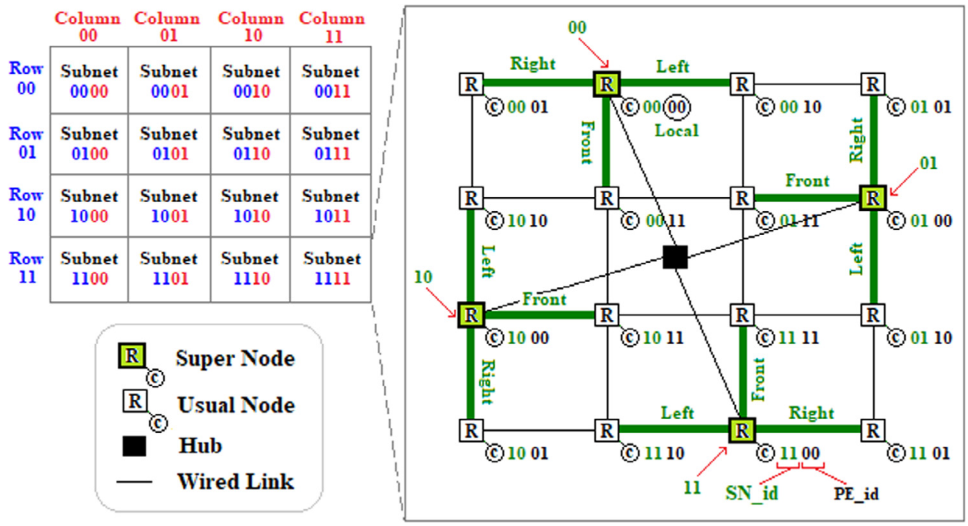

Fig. 15. An example of the numbering method for nodes.

Pseudo-code of routing algorithm

```
%% Router level
if (Subnet id of destination = Subnet id of source) then
    Look up table and find the path
    Send packet through this path
else
    if (Current node is not a super node) then
        Send packet to the super node
        Send packet from super node to the hub
    else
        Send packet to the hub
    end
end

%% Hub level
Look up table and find the path
Send packet through this path
```

Fig. 16. The pseudo-code of routing algorithm.

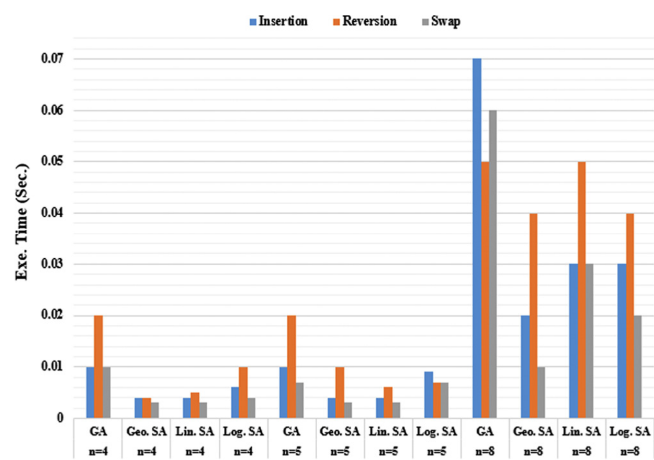

Fig. 17. Comparison of the execution time of the SA and GA algorithms in the different number of queens.

and the packet is transmitted. In case the source and destination nodes are on different subnets, data are first transmitted to the nearest super-node; then are transmitted to the hub. Each hub keeps routing information of the network in a routing table. Hence, the shortest path (in terms of the number of links) is selected and after a few steps, the data reach the related hub of the subnet which includes the destination node. However, in case the destination of data is a super-node, it will reach the destination within a hop. The pseudo-code for the routing algorithm is illustrated in Fig. 16.

5. Results

5.1. The results of optimization algorithms

The simulated annealing and genetic algorithms are evaluated using Matlab (R2012a). Due to the random nature of the algorithms, the mean value of the results obtained from 10 runs of the algorithm is reported. Fig. 17 shows the comparison of the execution time of the SA and GA algorithms in the different number of queens.

It can be argued that with the increase in the complexity of the problem, the execution time of the SA and GA algorithms also increases. Furthermore, in all cases, the best-obtained solution is equal to 0. It means that there are no attacks in the obtained solution. According to the results, it can be stated that the convergence speed of the simulated annealing algorithm, using the swap method and a geometric cooling scheme, is higher.

5.2. Wiring requirement of WiNoC

In [15,20], assuming a 20 mm $\times$ 20 mm die size in 65 nm technology, the length of wired links was estimated. Ganguly et al., in their proposed architecture, have used 1.25 mm wireline links to connect intra-subnet routers and 5 mm wireline links to connect hubs as well as hubs with intra-subnet routers [20]. Also, they have used 1.25 mm wireline links to connect routers of a wired flat mesh topology for NoC. However, instead of 1.25 mm wireline links, Deb et al. have used 2.5 mm wireline links to connect intra-subnet routers [15].

In a wired flat mesh topology with n nodes, a total number of required wired links is equal to $2 \times \left(n - \sqrt{n}\right)$ [17]. Thus, with 256 nodes, a total number of required wired links is 480. According to the estimated values in [15,20], for 256 nodes, Fig. 18 compares the number of required wired links for the proposed structures, flat mesh, and 2 previous proposed architectures. It should be

Please cite this article in press as: B. Bahrami, et al., A novel hierarchical architecture for Wireless Network-on-Chip, J. Parallel Distrib. Comput. (2018), https://doi.org/10.1016/j.jpdc.2018.02.032.

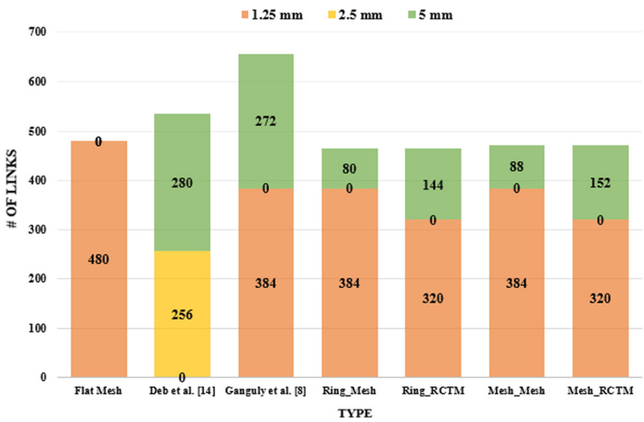

Fig. 18. Comparison of the number of required wired links for 7 different architectures.

Table 11
Simulation parameters.

Parameter	Setting
Clock frequency	2.5 GHz
Number of cores	256
Switching	Wormhole
Wireless communication	CNT Antennas
Number of virtual channels	4
Flit width	32 bits

Table 12
3-tuple traffic categories [22].

	Burstiness	Injection distribution	Hop distance
3tc0	Moderate	Hot-spot	Local
3tc1	High	Hot-spot	Local
3tc2	Moderate	Evened-out	Local
3tc3	High	Evened-out	Local
3tc4	Moderate	Hot-spot	Long-distance
3tc5	High	Hot-spot	Long-distance
3tc6	Moderate	Evened-out	Long-distance
3tc7	High	Evened-out	Long-distance

noted that, in these calculations, the wired links between cores and routers are ignored.

In the architecture proposed by Deb et al., the subnet topology is ring. In this topology, to connect 16 routers, 16 wireline links of 2.5 mm type are required. Thus, for 16 subnets, the total number of 2.5 mm wireline links is 256. Also, in this architecture, the topology of the second level of the hierarchy is a 4×4 mesh. Each hub, in addition to connecting to its adjacent hubs, connects to its subnet routers. Considering 24 links to connect inter-hub and 256 links to connect hubs to routers, in total, 280 wireline links of 5 mm type are needed.

In the architecture proposed by Ganguly et al., the subnet topology is mesh. Therefore, in each subnet, they have used 24 wireline links of 1.25 mm type to connect 16 routers. Thus, for 16 subnets, 384 wireline links of 1.25 mm type are needed. Also, the topology of the second level of the hierarchy is a ring. Considering 16 links to connect inter-hub and 256 links to connect hubs to routers, in total, 272 wireline links of 5 mm type are needed. In this paper, our main reference was the Ref. [20], and the calculations have been reported based on it. In the examined hierarchical structures, the number of the wired links required for the network is less than that of a flat mesh topology. Since the existence of a hierarchical structure eliminates a number of wired links. It is clear that the length of wired links between some of the links is different from that of other wired links. Four diagonal links in RCTM, super-nodes to the hubs, and inter-hub wireline links are 5 mm type. The rest of the links are 1.25 mm type. For RCTM subnet topology, in each subnet, there are 20 inter-routers wireline links of 1.25 mm type. Hence, for 16 subnets, 320 wireline links of 1.25 mm type are needed. For mesh subnet topology, in each subnet, there are 24 inter-routers wireline links of 1.25 mm type. Thus, for 16 subnets, 384 wireline links of 1.25 mm type are needed. In the second level of the hierarchy, for ring topology, 16 links to connect inter-hubs and $16 \times 4 = 64$ links to connect super-nodes to the hubs are needed. If subnet topology is RCTM, to these 80 wireline links of 5 mm type, $16 \times 4 = 64$ diagonal links are also added. For architectures with mesh topology in the second level of the hierarchy, 24 inter-hubs and $16 \times 4 = 64$ links to connect super-nodes to the hubs are needed. Again, if subnet topology is RCTM, to these 88 wireline links of 5 mm type, $16 \times 4 = 64$ diagonal links are also added.

5.3. Simulation results

5.3.1. Simulation parameters & traffic patterns

To evaluate the efficiency of the proposed structures for the WiNoC architecture, OMNET++ simulation tool with HNOCS [6] package is used. The parameters considered to get the simulation results are given in Table 11.

In this paper, the uniform random traffic was used as the synthetic traffic pattern and the 3-tuple traffic was used as a real application traffic pattern. Burstiness, injection distribution, and hop distance were the three significant factors producing a real application traffic pattern [40]. In this paper, the values suggested in [22] were used to model the three factors. Burstiness factor is used to model the frequency and amount of packet bursts. In fact, this factor indicates the characteristics of self-similarity in network traffic. In order to model the burstiness factor, the Hurst parameter is used with values between zero and one. In this paper, this factor was assumed in the moderate ($H = 0.65$) and high ($H = 0.9$) levels. For modeling the distribution of packets injected into the network, injection distribution factor is used. The injection distribution factor was investigated in the evened-out and hot-spot modes. Whereas 20% of the nodes received 68% of the total traffic in the evened-out injection, 10% of the nodes received 68% of the total traffic in the hot-spot injection. Also, the distance from source nodes to destination nodes is modeled using the hop distance factor. The hop distance factor was modeled in the long-distance and local modes. It was assumed that if traffic were the local type, 20% of the total traffic would pass more than four hops. However, if the traffic were of the long-distance type, 80% of the total traffic would pass more than eight hops. Based on the arguments given to the three factors establishing the real application traffic pattern, the results of their permutations will be eight traffic patterns which are listed in Table 12.

5.3.2. Hop count

In a mesh topology, the maximum distance will occur when the nodes located in the corners want to exchange data with each other. Nevertheless, in the proposed hierarchical structures, if both the source and destination are usual nodes and their subnets are in the far distance from each other, the maximum distance will occur. Fig. 19 compares the maximum distance between two nodes in a 16×16 wired mesh topology with those of the proposed hierarchical structures.

As shown in Fig. 19, the hierarchical structures were able to reduce the maximum distance between nodes. The improvement amounts in structures using ring topology and mesh topology for communicating among hubs were 70% and 76%, respectively. Fig. 20 depicts the average hop count between the source and destination nodes under different traffic patterns for the proposed structures.

Please cite this article in press as: B. Bahrami, et al., A novel hierarchical architecture for Wireless Network-on-Chip, J. Parallel Distrib. Comput. (2018), https://doi.org/10.1016/j.jpdc.2018.02.032.

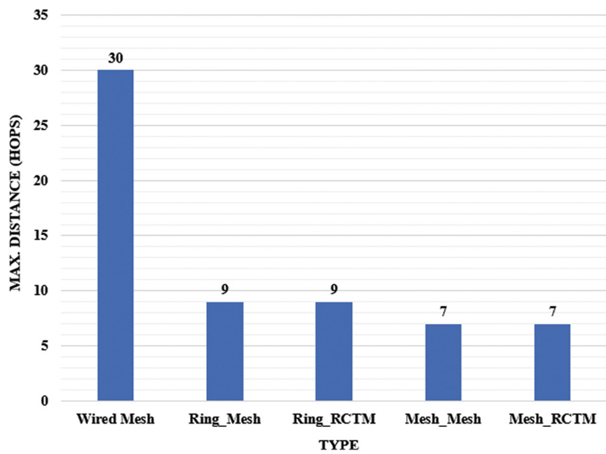

Fig. 19. Maximum distance comparison of the proposed hierarchical structures with that of a wired mesh topology.

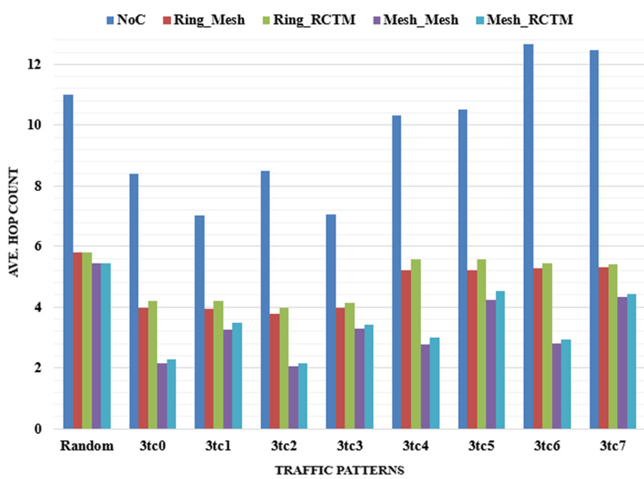

Fig. 20. Average hop count comparison of four structures with a wired mesh topology in NoC in different traffic patterns.

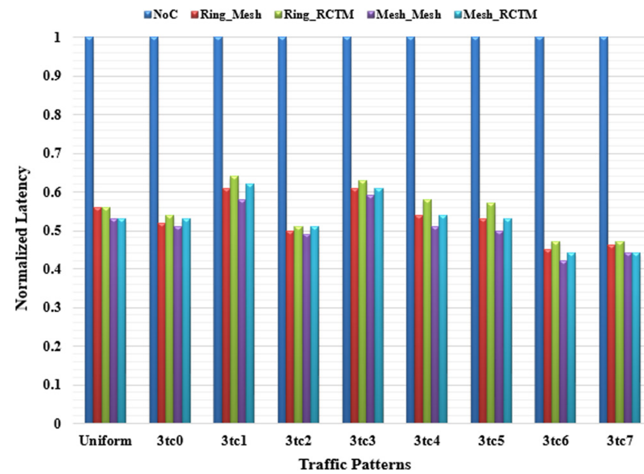

Fig. 21. Latency comparison of proposed structures in the normalized form with respect to latency in a wired mesh with 256 nodes.

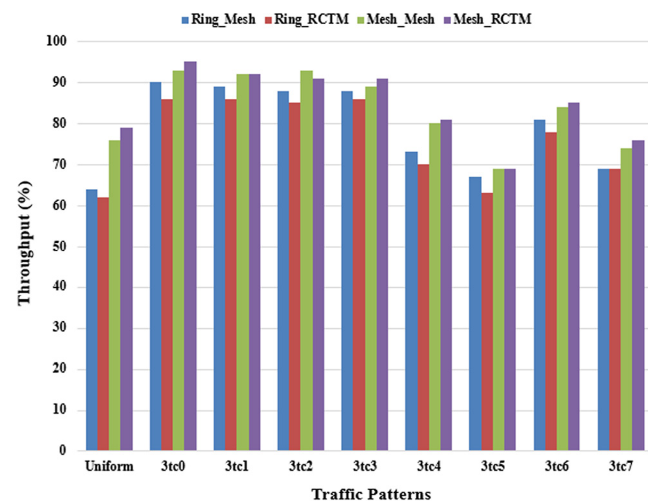

Fig. 22. Throughput comparison of proposed structures with 256 nodes in different traffic patterns.

It can be observed that proposed structures managed to reduce average hop count significantly better than a mesh topology in a traditional wired NoC. The results of the comparison of these structures in different traffic patterns indicated that the highest average hop count reduction was related to the Mesh_Mesh structure. It should be noted that the difference between Mesh_Mesh and Mesh_RCTM structures was negligible.

5.3.3. Latency

Fig. 21 relates to the comparison of the average latency of the proposed structures normalized to the latency of a mesh topology in a traditional wired NoC.

Regarding the latency comparison, Fig. 21 indicates that selecting mesh topology for the second level of the hierarchy had better results than the ring topology. Also, the comparison of the latency values of mesh and RCTM topologies for the first level of the hierarchy revealed that mesh topology should be considered as the best selection. However, it should be maintained that the differences of the values between the two topologies were insignificant. That is, in some cases, the latency values related to the mesh and RCTM were the same.

5.3.4. Throughput

Fig. 22 shows the throughput [14] comparison of the proposed hierarchical structures in different traffic patterns.

It can be observed that using a mesh topology for the second level of the hierarchy can result in a better throughput. Also, in the first level of the hierarchy, in most cases, the throughput values of the RCTM were better than mesh topology. Based on the obtained results, it can be stated that the highest packet loss can be observed in the second level of the hierarchy in the wired links leading to a wireless hub. Furthermore, using a routing algorithm of the greedy type which leads to the competition of packets for obtaining wireless links and also the limited capacity of wired links are the most important reasons for the packet loss in the second level of the hierarchy. To achieve high throughput and avoid packet loss, retransmission buffers or adaptive routing algorithms can be used in future work. Clearly, the implementation of each of these methods requires an additional cost.

5.4. Comparing the features of WiNoC architectures

5.4.1. The features of architectures

Table 13 is related to the features of proposed structures in this study and some previous architectures for 256 PEs.

5.4.2. Packet energy dissipation

The packet energy is the energy dissipated in delivering an entire packet from source to destination on an average. In proposed

Table 13
Comparing the features of proposed structures with some previous architectures for 256 PEs.

	Antenna	# of wired routers	# of hubs with wireless links	# of wireless links	Max. distance	Throughput (%)
Ganguly et al. [20]	CNT based	256	16	24	4	79.22
Deb et al. [15]	mm-wave based	256	6	15	5	83.76
Ring_Mesh	CNT based	256	4	6	9	77.78
Ring_RCTM	CNT based	256	4	6	9	76.11
Mesh_Mesh	CNT based	256	4	6	7	83.33
Mesh_RCTM	CNT based	256	4	6	7	84.33

Table 14
Energy dissipation components.

Packet types	Phrases	Definition	Energy dissipation components
Intra subnet	$E_{i,j}$	Energy dissipated by the *i*th packet on *j*th hop	Based on the source and destination addresses of a packet, a hop can include: • A router and a 2.5 mm wired link • A router and a 5 mm wired link
Inter subnet through fully wired paths	$E_{k,l}$	Energy dissipated by the *k*th packet on *l*th hop	Based on the source and destination addresses of a packet, a hop can include: • A router and a 2.5 mm wired link: from a usual node to a super node • A router and a 5 mm wired link: from a super node to a hub • A hub and a 5 mm wired link: from a hub to another hub • A hub and a 5 mm wired link: from a hub to a super node • A router and a 2.5 mm wired link: from a super node to a usual node
Inter subnet through hybrid paths	$E_{p,q}$	Energy dissipated by the *p*th packet on *q*th hop	Based on the source and destination addresses of a packet, a hop can include: • A router and a 2.5 mm wired link: from a usual node to a super node • A router and a 5 mm wired link: from a super node to a hub • A hub and a 5 mm wired link: from a hub to another wired hub • A hub and a wireless link: from a wireless hub to another wireless hub • A hub and a 5 mm wired link: from a hub to a super node • A router and a 2.5 mm wired link: from a super node to a usual node

architectures, based on the source and destination addresses of a packet, the transmission mode will have one of the following modes:

- Intra subnet
- Inter subnet through fully wired paths
- Inter subnet through hybrid paths (wired and wireless links).

Details of energy dissipation components are presented in Table 14.

Using formula 1, the average energy dissipation of a packet can be calculated. Details of the formula are given below.

Average Packet Energy Dissipation

$$= \frac{\sum_{i=1}^{n1}\sum_{j=1}^{h1} E_{i,j} + \sum_{k=1}^{n2}\sum_{l=1}^{h2} E_{k,l} + \sum_{m=1}^{n3}\sum_{n=1}^{h3} E_{p,q}}{n1+n2+n3} \quad (1)$$

$n1$: Total number of packets of the first type of transmission
$n2$: Total number of packets of the second type of transmission
$n3$: Total number of packets of the third type of transmission
So that: (Total number of packets $= n1+n2+n3$)
$h1$: Maximum number of hops for the ith packet
$h2$: Maximum number of hops for the kth packet
$h3$: Maximum number of hops for the pth packet.

Fig. 23 is related to the average packet energy dissipation normalized to the architecture proposed by Deb et al. [15].

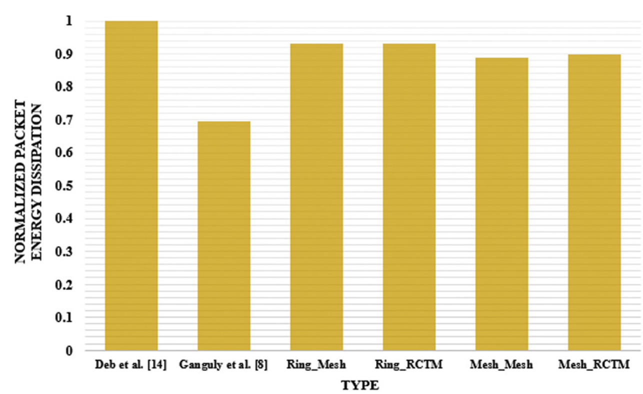

Fig. 23. Normalized packet energy dissipation for different architectures.

5.4.3. Area overhead

Adding wireless equipment to a network will impose an additional area. In [15], the total area overhead per wireless transceiver has been reported 0.3 mm^2 for the selected frequency range. In [20], this value is equal to 0.0001 for 1 wireless with 24 frequency channels. The reasons for this are the type of antenna and transceiver circuits. The used antenna in [15] is compatible with CMOS technology, while the used antenna in [20] is CNT-based. In [20], area overhead of wireless ports is reported in various frequency states. But, based on the results, the use of 24 wireless links with 1 frequency channel for each one is proposed. In this paper, based on the reported values in [20], 6 wireless links with 4 frequency channels are used. Fig. 24 is related to the total area overhead of wireless ports for this work and the proposed architecture by Ganguly et al.

5.5. The results of the analytic hierarchy process

In Section 3, pairwise comparison method was explained for the criterion of maximum distance. For other criteria, the pairwise comparison matrix elements have been set based on the average results of different traffic patterns for a criterion. Pairwise comparison matrices of other criteria are defined in Tables 15–17. Also, the priority vector for each criterion is reported in Table 18.

Table 15
The pairwise comparison matrix of average hop count.

Average hop count	Ring_Mesh	Ring_RCTM	Mesh_Mesh	Mesh_RCTM
Ring_Mesh	1	2/1	2/4	2/3
Ring_RCTM	1/2	1	1/4	1/3
Mesh_Mesh	4/2	4/1	1	4/3
Mesh_RCTM	3/2	3/1	3/4	1

Table 16
The pairwise comparison matrix of latency.

Latency	Ring_Mesh	Ring_RCTM	Mesh_Mesh	Mesh_RCTM
Ring_Mesh	1	2/1	2/3	2/2
Ring_RCTM	1/2	1	1/3	1/2
Mesh_Mesh	3/2	3/1	1	3/2
Mesh_RCTM	2/2	2/1	2/3	1

Table 17
The pairwise comparison matrix of throughput.

Throughput	Ring_Mesh	Ring_RCTM	Mesh_Mesh	Mesh_RCTM
Ring_Mesh	1	2/1	2/3	2/4
Ring_RCTM	1/2	1	1/3	1/4
Mesh_Mesh	3/2	3/1	1	3/4
Mesh_RCTM	4/2	4/1	4/3	1

Results of the pairwise comparisons of the criteria are reported in Table 19.

The final weight of each alternative are as follows:

Ring_Mesh: $(0.1\times0.125)+(0.2\times0.2)+(0.4\times0.25)+(0.3\times0.2)=0.2125$

Ring_RCTM: $(0.1\times0.125)+(0.2\times0.1)+(0.4\times0.125)+(0.3\times0.1)=0.1125$

Mesh_Mesh: $(0.1\times0.375)+(0.2\times0.4)+(0.4\times0.375)+(0.3\times0.3)=0.3575$

Mesh_RCTM: $(0.1\times0.375)+(0.2\times0.3)+(0.4\times0.25)+(0.3\times0.4)=0.3175$.

The priority ranking of alternatives is reported in Table 20.

According to the ranking, the best hierarchical structure is Mesh_Mesh.

6. Conclusions and future work

In this paper, hybrid hierarchical structures were proposed to enhance the efficiency of a traditional mesh topology in network-on-chip. For this purpose, the combination of a number of topologies with similar architectures was investigated. Also, two new methods were proposed for selection of wireless hub locations: the hub number-based selection and the n-queens problem based approach. Since the n-queens problem is one of the NP-hard problems, the SA and GA algorithms were used to solve the problem. The proposed structures in this study had fewer wireless hubs. Also, hubs can provide communications with subnets using fewer wired links. Based on the simulation results, it can be argued that the hierarchical structures for the wireless NoC architecture can enhance the performance of the network-on-chip. After comparing the proposed structures using the analytic hierarchy process, it can be stated that a hierarchical structure in which mesh topology is used in both levels, is the best choice. In the future work, the traffic patterns can be used for decision-making. Also, to improve the quality of results, it is suggested that the use of fault-tolerant routing algorithms in the proposed structure should be investigated.

Table 20
The priority ranking of alternatives.

Alternative	Priority
Mesh_Mesh	0.3575
Mesh_RCTM	0.3175
Ring_Mesh	0.2125
Ring_RCTM	0.1125
Total	1

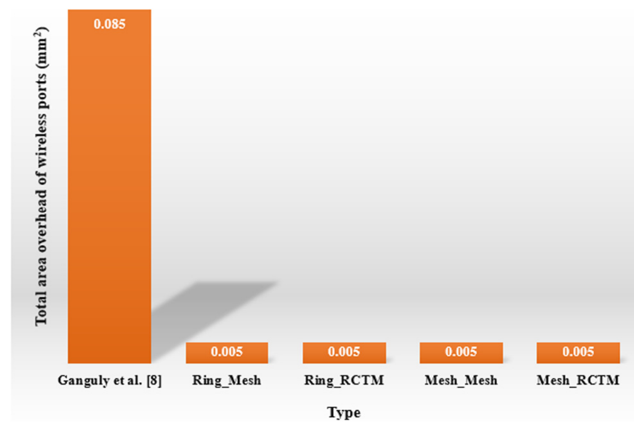

Fig. 24. Total area overhead of wireless ports.

Table 18
The priority vector for each criterion.

	Maximum distance	Average hop count	Latency	Throughput
Ring_Mesh	0.125	0.2	0.25	0.2
Ring_RCTM	0.125	0.1	0.125	0.1
Mesh_Mesh	0.375	0.4	0.375	0.3
Mesh_RCTM	0.375	0.3	0.25	0.4

Table 19
Results of the pairwise comparisons of the criteria.

	Max. distance	Ave. hop count	Latency	Throughput	Priority vector
Max. distance	1	1/2	1/4	1/3	0.1
Ave. hop count	2/1	1	2/4	2/3	0.2
Latency	4/1	4/2	1	4/3	0.4
Throughput	3/1	3/2	3/4	1	0.3

References

[1] S. Abadal, M. Nemirovsky, E. Alarcón, A. Cabellos-Aparicio, Networking challenges and prospective impact of broadcast-oriented wireless networks-on-chip, in: Proceedings of the ACM/IEEE NoCS, 2015.

[2] A.M.P. Amorim, P.A.C. Oliveira, H.C. Freitas, Performance evaluation of single- and multi-hop wireless networks-on-chip with NAS Parallel Benchmarks, J. Braz. Comput. Soc. (2015).
[3] B. Bahrami, M.A.J. Jamali, S. Saeidi, Proposing an optimal structure for the architecture of wireless networks on chip, Telecommun. Syst. 62 (1) (2016) 199–214.
[4] B. Bahrami, M.A.J. Jamali, S. Saeidi, A demand-based structure for the architecture of wireless networks on chip, Wirel. Pers. Commun. 96 (1) (2017) 455–473.
[5] J. Bell, B. Stevens, A survey of known results and research areas for n-queens, Discrete Math. 309 (1) (2009) 1–31.
[6] Y. Ben-Itzhak, E. Zahavi, I. Cidon, A. Kolodny, HNOCS: Modular open-source simulator for Heterogeneous NoCs, in: SAMOS Conference, 2012, pp. 51–57.
[7] L. Benini, G. De Micheli, Network on chip: a new paradigm for systems on chip design, in: Proceedings of Design, Automation and Test in Europe Conference and Exhibition, 2002, pp. 418–419.
[8] P.J. Burke, S. Li, Z. Yu, Quantitative theory of nanowire and nanotube antenna performance, IEEE Trans. Nanotechnol. 5 (4) (2006) 314–334.
[9] L. Carloni, P. Pande, Y. Xie, Network-on-Chip in emerging interconnect paradigms: Advantages and challenges, in: Proceedings of 3rd ACM/IEEE International Symposium Network-on-Chip, 2009, pp. 93–102.
[10] M. Chang, J. Cong, A. Kaplan, M. Naik, G. Reinman, E. Socher, S.W. Tam, CMP network-on-chip overlaid with multi-band RF-interconnect, in: Proceedings of IEEE International Symposium High-Performance Computer Architecture (HPCA), 2008, pp. 191–202.
[11] A. Chariete, M. Bakhouya, J. Gaber, M. Wack, A design space exploration methodology for customizing on-chip communication architectures: Towards fractal NoCs, Integr. VLSI J. 50 (2015) 158–172.
[12] A. Chien, A cost and speed model for k-ary n-cube wormhole routers, IEEE Trans. Parallel Distrib. Syst. 9 (2) (1998) 150–162.
[13] P. Dai, J. Chen, Y. Zhao, Y.H. Lai, A study of a wire–wireless hybrid NoC architecture with an energy-proportional multicast scheme for energy efficiency, Comput. Electr. Eng. 45 (2015) 402–416.
[14] W. Dally, B. Towles, Principles and Practices of Interconnection Networks, Morgan Kaufmann Publishers, 2003.
[15] S. Deb, K. Chang, X. Yu, S.P. Sah, M. Cosic, A. Ganguly, P.P. Pande, B. Belzer, D. Heo, Design of an energy-efficient CMOS-Compatible NoC architecture with millimeter-wave wireless interconnects, IEEE Trans. Comput. 62 (12) (2013) 2382–2396.
[16] S. Deb, A. Ganguly, K. Chang, P. Pande, B. Belzer, D. Heo, Enhancing performance of network-on-chip architectures with millimeter-wave wireless interconnects, in: The 21st IEEE International Conference on Application-specific Systems Architectures and Processors, 2010.
[17] J. Duato, S. Yalamanchili, L. Ni, Interconnection Networks an Engineering Approach, Morgan Kaufmann Publishers, 2003.
[18] H. El-Rewini, M. Abd-El-Barr, Advanced Computer Architecture and Parallel Processing, John Wiley & Sons, 2005.
[19] B. Floyd, C.M. Hung, K. O, Intra-chip wireless interconnect for clock distribution implemented with integrated antennas, receivers, and transmitters, IEEE J. Solid-State Circuits 37 (5) (2002) 543–552.
[20] A. Ganguly, K. Chang, S. Deb, P.P. Pande, B. Belzer, C. Teuscher, Scalable hybrid wireless network-on-chip architectures for multicore systems, IEEE Trans. Comput. 60 (10) (2011) 1485–1502.
[21] J. Holland, Adaptation in Natural and Artificial Systems, University of Michigan Press, 1975.
[22] W.H. Hu, C. Wang, N. Bagherzadeh, Design and analysis of a mesh-based wireless network-on-chip, J. Supercomput. 71 (8) (2015) 2830–2846.
[23] International Technology Roadmap for Semiconductors, (ITRS, 2007).
[24] A. Jagota, Optimization by reduction to maximum clique, in: IEEE International Conference on Neural Networks, 1993, pp. 1526–1531.
[25] M.A.J. Jamali, A. Khademzadeh, MinRoot and CMesh: Interconnection architectures for network-on-chip systems, Int. J. Electr. Comput. Energ. Electron. Commun. Eng. 3 (6) (2009) 1303–1308.
[26] A.J. Karkar, J.E. Turner, K. Tong, R. Al-Dujaily, T. Mak, A. Yakovlev, F. Xia, Hybrid wire-surface wave interconnects for next-generation networks-on-chip, IET Comput. Digit. Tech. 7 (6) (2013) 294–303.
[27] K. Kempa, J. Rybczynski, Z. Huang, K. Gregorczyk, A. Vidan, B. Kimball, J. Carlson, G. Benham, Y. Wang, A. Herczynski, Z. Ren, Carbon nanotubes as optical antennae, Adv. Mater. 19 (2007) 421–426.
[28] K. Kim, H. Yoon, K. O, On-chip wireless interconnection with integrated antennas, in: Electron Devices Meeting, 2000, pp. 485–488.
[29] S. Kirkpatrick, C. Gelatt Jr., M. Vecchi, A. McCoy, Optimization by simulated annealing, Science 220 (4598) (1983) 671–679.
[30] A. Mineo, M. Palesi, G. Ascia, V. Catania, Exploiting antenna directivity in wireless NoC architectures, Microprocess. Microsyst. 43 (2016) 59–66.
[31] J. Murray, P. Wettin, P. Pande, B. Shirazi, Sustainable Wireless Network-on-Chip Architectures, Morgan Kaufmann Publishers, 2016.
[32] Y. Nourani, B. Andresen, A comparison of simulated annealing cooling strategies, J. Phys. A: Math. Gen 31 (1998) 8373–8385.
[33] P.P. Pande, A. Ganguly, K. Chang, C. Teuscher, Hybrid wireless network on chip: A new paradigm in multi-core design, in: 2nd International Workshop on Network on Chip Architectures, 2009, pp. 71–76.
[34] B. Parhami, Introduction To Parallel Processing Algorithms and Architectures, Kluwer Academic Publishers, 2002.
[35] V. Pavlidis, E. Friedman, 3-D Topologies for networks-on-chip, in: IEEE International SOC Conference, 2006, pp. 285–288.
[36] A. Rezaei, M. Daneshtalab, F. Safaei, D. Zhao, Hierarchical approach for hybrid wireless Network-on-chip in many-core era, Comput. Electr. Eng. 51 (2016) 225–234.
[37] T.L. Saaty, A scaling method for priorities in hierarchical structures, J. Math. Psych. 15 (1977) 57–68.
[38] T.L. Saaty, The Analytic Hierarchy Process, McGraw-Hill, 1980.
[39] A. Shacham, K. Bergman, L. Carloni, Photonic networks-on-chip for future generations of chip multiprocessors, IEEE Trans. Comput. 57 (9) (2008) 1246–1260.
[40] V. Soteriou, N. Eisley, H. Wang, B. Li, L.S. Peh, Polaris: A system-level roadmap for on-chip interconnection networks, in: International Conference on Computer Design, 2006, pp. 134–141.
[41] M. Tomassini, M. Giacobini, C. Darabos, Evolution and dynamics of small-world cellular automata, Complex Syst. 15 (4) (2005) 261–284.
[42] C. Wang, W.H. Hu, N. Bagherzadeh, A Wireless network-on-chip design for multicore platforms, in: Proceedings of 19th Euromicro International Parallel, Distributed and Network-Based Processing (PDP) Conference, 2011, pp. 409–416.
[43] C. Wang, W.H. Hu, N. Bagherzadeh, A load-balanced congestion-aware wireless network-on-chip design for multicore platforms, Microprocess. Microsyst. 36 (7) (2012) 555–570.
[44] S. Wang, T. Jin, Wireless network-on-chip: a survey, J. Eng. (2014).
[45] D. Zhao, Y. Wang, SD-MAC: Design and synthesis of a hardware-efficient collision-free QoS-aware MAC protocol for wireless network-on-chip, IEEE Trans. Comput. 57 (9) (2008) 1230–1245.
[46] D. Zhao, Y. Wang, J. Li, T. Kikkawa, Design of multi-channel wireless noc to improve on-chip communication capacity, in: Fifth ACM/IEEE International Symposium on Network-on-Chip, 2011, pp. 177–184.

Bahareh Bahrami received her B.Sc. in Computer Engineering from Islamic Azad University, Khoy branch, Iran, in 2009. She received her M.Sc. in Computer Engineering from Islamic Azad University, Tabriz branch, Iran, in 2013. Her research interests include network-on-chip, VLSI design and computer architecture.

Mohammad Ali Jabraeil Jamali received his B.Sc. in Electrical Engineering from Urmia University, Urmia, Iran, the M.Sc. in Electrical Engineering from Tabriz University, Tabriz, Iran, the M.Sc. in Computer Engineering from Islamic Azad University, Science and Research branch, Tehran, Iran and the Ph.D. in Computer Engineering from Islamic Azad University, Science and Research branch, Tehran, Iran, in 1994, 1997, 2003 and 2009, respectively. He is an assistant professor of Computer Engineering at Islamic Azad University, Shabestar branch. He is the author/co-author of more than 50 publications in technical journals and conferences. His current research interests are processor and computer architectures, chip multiprocessors, multiprocessor systems-on-chip, networks on chip, ad hoc and sensor networks.

Shahram Saeidi was born in Tabriz, Iran, 1973. He earned his Ph.D. and M.Sc. degrees in Industrial Engineering, and B.Sc. degree in Computer Software Engineering. He is a professor of Computer Engineering Department, Islamic Azad University, Tabriz Branch, Tabriz, Iran.

Please cite this article in press as: B. Bahrami, et al., A novel hierarchical architecture for Wireless Network-on-Chip, J. Parallel Distrib. Comput. (2018), https://doi.org/10.1016/j.jpdc.2018.02.032.