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Topology generation and performance enhancement based on channel assignment optimization for hybrid wireless NoC with large system size

Jianhua Li*, Han Li, Yongliang Hu, Gaobiao Wu

Institute of Computer Application, Taizhou University, 317000, China

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ABSTRACT

To achieve the efficient topology generation of upper-layer network in hybrid wireless NoC with large system size, a method of topology generation and performance enhancement based on channel assignment optimization is proposed. The method is implemented under certain signal-to-interference plus noise ratio (SINR) and strict resource budget by establishing relevant models of power consumption and interference for hybrid wireless NoC. A communication protocol with low overhead based on weighted conflict graph and two-level wireless token arbitration mechanism is designed for hybrid WiNoC with large system size. The designed protocol could handle channel contention and reduce the waiting time to get access to a wireless channel effectively. It improves obviously the frequency channel utilization. The experimental simulation demonstrates that the resulting topology generated by channel assignment optimization outperforms the conventional counterparts in terms of achievable throughput, power efficiency and latency at the cost of little area overhead.

1. Introduction

Network-on-Chip (NoC) has emerged as an interconnection and communication architecture for the complex SoC paradigm [1]. The NoC has appeared as a good alternative for global interconnects due to their optimized electrical properties, such as better performance in terms of power, delay, bandwidth, and scalability compared to buses and global interconnects [2]. However, the performance limitations such as high latency and power consumption due to planar multihop wired links hinder seriously the further performance enhancement of multicore SoC with the increasing complexity [3]. Recently, by integrating miniaturized on-chip antennas and transceivers, the Wireless NoC (WiNoC) has been proposed as a promising solution to enable intra-chip wireless interconnection and communication with a few tens to a few hundreds of GHz bandwidth [4–6]. Owing to the lower design complexity, higher performance gains in terms of transmission performance and power consumption, the hybrid wired/wireless WiNoC architectures with millimeter-wave interconnects (mWNoC) currently dominate the research in the wireless NoC [7–9]. Nevertheless, the hybrid WiNoC still faces some problems of topology design besides the technological challenges including the design of transceiver components and integration of on-chip antennas.

Firstly, the topology design of hybrid WiNoC suffers from resource limitations such as the total wireless spectrum and available number of sub-channels. For example, in [10], it is demonstrated that only three non-overlapping channels were created with on-chip mm-wave wireless links. There are 24 different frequency channels created through the carbon nanotubes (CNT) antennas for the WiNoC architecture designed with THz/optical frequency range wireless links (THzNoC). Although the THzNoC shows better performance than mWNoC, the performance improvement of hybrid WiNoC with large system size will suffer from the limited number of wireless links depending on the available number of distinct frequency channels. What is more, THzNoC working on 24 wireless channels still faces some challenges in manufacturing, integration, layout and reliability of CNT devices. By contrast, the mWNoC is CMOS-compatible. Similarly, a total of 16 available channels [5,12] is insufficient for the large-scale on-chip wireless network. Secondly, the wireless nodes will cause additional power consumption and area overhead arising from embedding wireless communication components. Subsequently, the topology design of hybrid WiNoC should be implemented under strict physical constraints from the area overhead of wireless nodes (i.e., on-chip antennas, transceivers, etc.). Thirdly, the wireless links encounter channel interference (inclusive of inter-channel interference and co-channel interference), which remains unresolved [11,12] and results in performance limitation in terms of network capacity and data transmission rates [13] in the hybrid WiNoC.

From the perspective of low-power design, by improving network connectivity of hybrid WiNoC, it is quite effective to increase network capacity and reduce communication power consumption with positive relation to average hop count. There is no doubt that the fully

* Corresponding author.
E-mail address: ljh2007@tzc.edu.cn (J. Li).

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connected wireless network in the upper layer of hybrid WiNoC could achieve the least hop count and lowest communication power consumption. Despite all this, it will cause increasing in the number of wireless links sharing the same frequency channel due to the limitation of available number of wireless channels. For example, in the case of hybrid WiNoC system with 12 wireless links working on the above-mentioned three non-overlapping channels, there will be four wireless links sharing the same frequency channel on average. However, the wireless links working in the interference range will interfere with each other if they are on the same frequency channel [14]. That is to say if two links are within the interference range of each other, they can transmit or receive simultaneously only if they use different channels. Similarly, owing to the low parallelism arising from link interference [13], the performance improvement in transmission delay and throughput will be limited in the certain degree for hybrid WiNoC. From the perspective of low-interference design, we should decrease the number of wireless links sharing the same frequency channel to reduce network interference [13], which in turn results in lower network connectivity. Thus it will increase the power consumption of hybrid WiNoC. It can be seen that power consumption and network interference interact with each other: the more connectivity is achieved, but the more interference is induced. However, by reasonable wireless link placement and channel assignment (CA) under limited number of wireless channels, it is possible to properly increase the number of wireless links, and at the same time reduce power consumption and link interference [15].

An mWNoC architecture, which can accommodate single or three simultaneous frequency channels resulting in further improvement of overall performance, is designed by optimizing the wireless interfaces (WIs) under the constraints that a single hub (namely, wireless router, WR) could have a maximum of one WI (denoted as MOWI) and each WI in the network is assigned one of the three channels [11]. Owing to those design constraints, there will be only maximum of one WR working on particular frequency channel at any given instant of time. That is to say, each node has maximum of one simultaneously transmitting wireless links at a time. It is unreasonable to improve the overall performance especially for the hot wireless nodes. Furthermore, the WIs sharing the same channel form a cluster and a simple token passing protocol as the arbitration policy is used to handle co-channel contention and interference in the mWNoC, but it does not scale well with an increase in the number of wireless nodes, and the excessive wireless links sharing the same frequency channel will cause higher token returning period [16] and lower parallelizability between the links for hybrid WiNoC with large system size. As illustrated in [17], for a 64-core system, WiNoC uses twelve WIs in total with four WIs operating on each of the 3 wireless channels. As can been seen in Fig. 1a, each WR has only a single WI assigned one of the three channels (channel $c1$, $c2$ and $c3$) in the mWNoC for a 36-core system. There are three clusters and each cluster is formed by 3 WIs sharing the same channel. It is observed that it has at most 3 simultaneously transmitting wireless links over different channels at a time for any size mWNoC, such as link $l_{(1,2)}$, $l_{(6,7)}$ and $l_{(3,5)}$ (or link $l_{(1,2)}$, $l_{(6,8)}$ and $l_{(4,5)}$), concurrently. The $l_{(1,\ 2)}$ is defined in Section 3.1.

We can predict that the cluster will grow larger because of enormous number of WIs assigned the same channel for a 512-core system or larger system. However, according to previous research work in wireless mesh networks [14], the architecture of multi-radio with multiple channels assigned to every wireless router nodes could enable multiple transmissions or receptions concurrently. By using the channel assignment optimization (CAO), the neighboring wireless links assigned to different channels can carry traffic free of interference, so that it can dramatically reduce the transmission delay and improve the network throughput up to several-fold advancement [15]. Subsequently, it is very attractive to implement the topology design based on CAO while deploying multiple WIs (multi-WI) to the WR. Fig. 1b shows the WiNoC topology with multi-WI based on channel assignment optimization. It can be seen that the maximum number of simultaneously transmitting wireless links at a time is up to six links in the optimal topology (i.e., $l_{(1,2)}$, $l_{(3,4)}$, $l_{(7,8)}$, $l_{(2,3)}$, $l_{(8,9)}$ and any one link working on channel $c3$). The average token returning period will also decrease due to the existing more parallel links. Correspondingly, the frequency channel utilization will be improved greatly as frequency reuse at a time. Furthermore, each WR with a single WI has maximum of one simultaneously transmitting wireless links at a time (e.g., only $l_{(1,2)}$ for hot node wr_1 in Fig. 1a). The wr_1 is defined in Section 3.1. By contrast, each WR with multi-WI could have multiple transmitting wireless links simultaneously at a time (e.g., $l_{(1,2)}$, $l_{(2,5)}$ and $l_{(2,9)}$ for hot node wr_2 in Fig. 1(b)). Fig. 1c shows the structure of wr_3 with two wireless input/output ports (WI1 and WI2), and the number of WIs depends on the number of wireless channels and the location of WR.

According to the analysis mentioned above, the reasonable and valid channel assignment appears particularly important to design hybrid WiNoC with low interference and high parallelism between links. So far, no effort has been made to design the low interference and high parallelism WiNoC with large system size, and it is a somewhat challenging topic and seldom studied. Therefore, we propose a design method based on optimal wireless link placement and channel assignment under limited wireless resources to generate high-performance topology for hybrid WiNoC with large system size.

Major contributions of this paper are as follows:

(1) We establish mathematical analysis models of power consumption

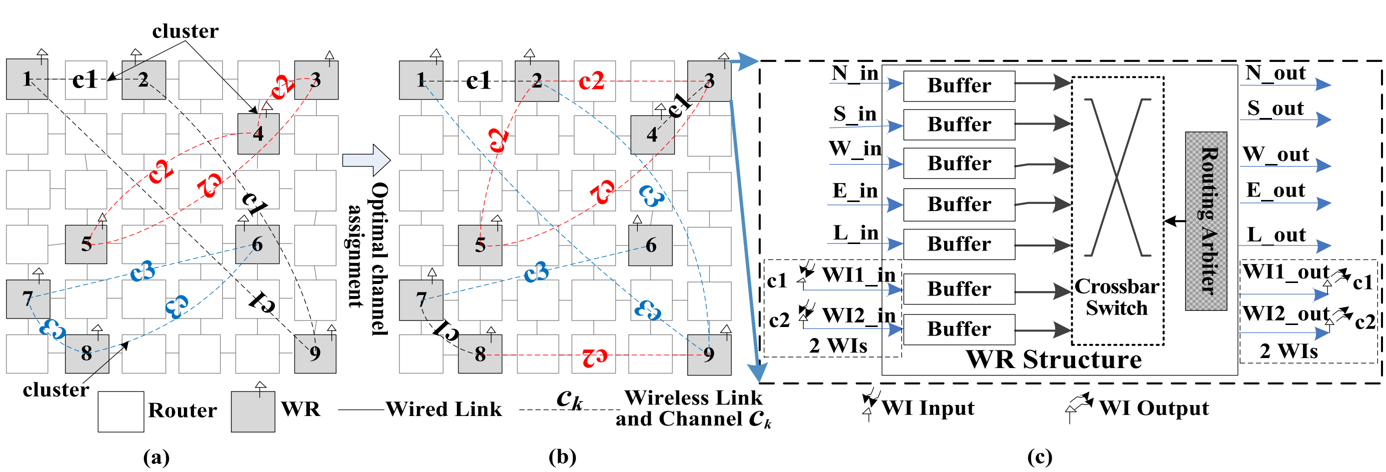


Fig. 1. Topology for a 36-core system and the WR structure of hybrid wireless NoC: (a) mWNoC topology with single WI. (b) WiNoC topology with multi-WI based on channel assignment optimization. (c) WR structure.

and network interference for the upper-layer network of hybrid WiNoC based on the weighted conflict graph under certain SINR and strict wireless resource constraints.

(2) It is the first work in hybrid WiNoC with large system size to propose improving parallelism of communication links and reducing network interference based on channel assignment optimization under limited wireless resources to implement efficient topology generation with multi-WI. Meanwhile, this work further improves overall performance such as the power consumption, throughput and communication latency.

(3) To handle the channel contention and interference, a two-level wireless token arbitration mechanism with low overhead based on the weighted conflict graph has been designed accordingly to grant the channel access to a particular WI, and it reduces the waiting time to get access to a wireless channel in hybrid WiNoC with large system size. Furthermore, the utilization of frequency channel has been improved greatly by increasing parallel communication links and implementing traffic balance between wireless channels. We present simulation results to evaluate the performance of topology generated by channel assignment optimization. The area overhead is also quantified.

2. Related work

There have been several works to address the topology generation and performance enhancement by placement optimization of wireless router and links in the upper layer of hybrid WiNoC. It has been shown that the optimal locations for WRs could be searched quickly by using the SA optimization technique, so that the average distance as cost function is minimized [3]. In [9], a method for the insertion and placement optimum of wireless links based on SA heuristics is presented to obtain a lower average distance as the metric in THzNoC. Similarly, the SA-based optimization procedure for obtaining optimum number of WIs and their suitable placement has been discussed in mWNoC [11]. For the irregular topology design of hybrid application-specific WiNoC, a heuristic algorithm after building the performance analysis model based on the theory of Network Calculus has been adopted to resolve the problem of wireless link allocation [18]. A WRs placement algorithm based on SA has been devised to minimize communication latency and shows the significant improvement hybrid WiNoC [19]. However, in the above schemes a single-frequency channel is used only once (denoted as SFC−OO) while channels are assigned to wireless links [3,9,18,19]. Although the channel assignment scheme that can tackle the co-channel interference is fairly intuitive, there will be insufficient wireless links depending on the available frequency channels for the high performance topology design of hybrid WiNoC with large system size. Similarly, it will limit the overall performance improvement in power consumption and reduce the frequency utilization greatly due to the low connectivity of hybrid WiNoC. Additionally, to improve maximum sustainable load of NoC, a reliable 2-D waveguide communication fabric is proposed to alleviate the performance degradation due to high error rates of the wireless communication channel in hybrid wireless NoC [20]. A wireless NoC where all cores share a single broadband channel is presented, and such design is conceived to provide low latency and ordered delivery for multicast/broadcast traffic [21].

In our work, our interest is to implement the topology generation with multi-WI and performance enhancement based on channel assignment optimization under strict wireless resource constraints, so that the optimal topology could achieve significant improvement in power efficiency, throughput, network interference and parallelism for wireless NoC with large system size.

3. Relevant mathematical models of topology generation for WiNoC

In this section we describe the major design issues that include wireless link placement and channel assignment optimization for topology generation of WiNoC larger system size. Besides, this section also clarifies the relevant mathematical models, such as the power consumption analysis model based on unique connectivity matrix and the system interference model using weighted conflict graph. The hybrid network collaborates traffic load to optimize power consumption, network interference and throughput under limited wireless resources.

3.1. Issues description

The hybrid WiNoC topology consists of lower-layer wired network equipped with routers and upper-layer wireless network equipped with wireless routers [11,12,18]. Some wired routers have been replaced with WRs by using effective placement strategy. The neighboring routers are connected by traditional wired links, and the single-hop long-range wireless links are used to connect the distant WRs. As shown in Fig. 1c, each WR includes five input/output ports (E, S, W, N and L), and several WIs for data input/output. The two WRs connected by wireless link could communicate with each other by using WIs, which include antenna and transceiver circuits principally [11,16]. The input/output ports of WR are connected to the crossbar switch so that the data flits from wired ports can be forwarded to wireless ports and vice versa. But flits from wireless input ports are prohibited to be forwarded to the wireless ports [18]. Thus flits can be transmitted in maximum of one-hop wireless link through upper-layer wireless network of hybrid WiNoC. In order to describe the topology generation method based on channel assignment optimization, some definitions are as follows:

Definition 1 (*(Topology Connection Graph (TCG))*). TCG(R, E) is a directed graph representing the connection status of wired router nodes and communication links in wired 2D-Mesh NoC. The R is the set of N wired routing nodes, $|R| = N$. The edge E is the set of communication links. $e(i, j) = (r_i, r_j)\in E$ represents the wired link between wired router nodes r_i and $r_j(r_i, r_j\in R)$.

Definition 2 (*(Wireless Topology Connection Graph (WTCG))*). WTCG($\hat{W}$, L) represents the connection status of WR nodes in the upper-layer of hybrid WiNoC, the $\hat{W}$ is the set of N_{wr} wireless routing nodes, $|\hat{W}| = N_{\mathrm{wr}}$. The edge L is the set of N_l wireless links, $|L| = N_l$. Given wr_i represents the wireless router node number i, $l_{(i,j)} = (\mathrm{wr}_i, \mathrm{wr}_j)\in L$ represents the existing wireless link between wireless nodes wr_i and $\mathrm{wr}_j(\mathrm{wr}_i, \mathrm{wr}_j\in\hat{W})$.

Definition 3 (*($C = \{c1, c2,\ldots,ck\}$)*). represents the set of available channels in hybrid WiNoC, and $|C| = k$. $\check{R}_i$ is the available number of WIs for wireless router node wr_i. Each WI has usually one channel, thus the maximum number of channels assigned to wr_i is $\check{R}_i$, where $\check{R}_i\in[1, k]$.Usually, the conflict graph has generally been used to represent the set of pairs of communication links that interfere with each other and be on the same channel in the previous works [13–15]. To depict the link interference, in this work, we use the improved weighted conflict graph. Now given a set of vertices V_c corresponding to the wireless links in L, namely:

$$V_c = \{l_{(i,j)}|(\mathrm{wr}_i, \mathrm{wr}_j) \in L\}$$

Definition 4 (*(Weighted Conflict Graph (WCG))*). WCG(V_c, E_c, Q_c) is defined as a weighted conflict graph of WTCG($\hat{W}$, L), each vertex in V_c corresponding to a link in L. The E_c is the set of conflict edges. Given two vertices a, $b\in V_c$ correspond two links $l_{(i,j)}$ and $l_{(u,v)}$ in WTCG, respectively. $\bar{O}_{ab}\in Q_c$ is the weight value on edge $(a, b) = (l_{(i,j)}, l_{(u,v)})$ and equals to the product of two normalized traffics over links $l_{(i,j)}$ and $l_{(u,v)}$.

The WCG has an edge $(a, b)\in E_c$ connecting two corresponding

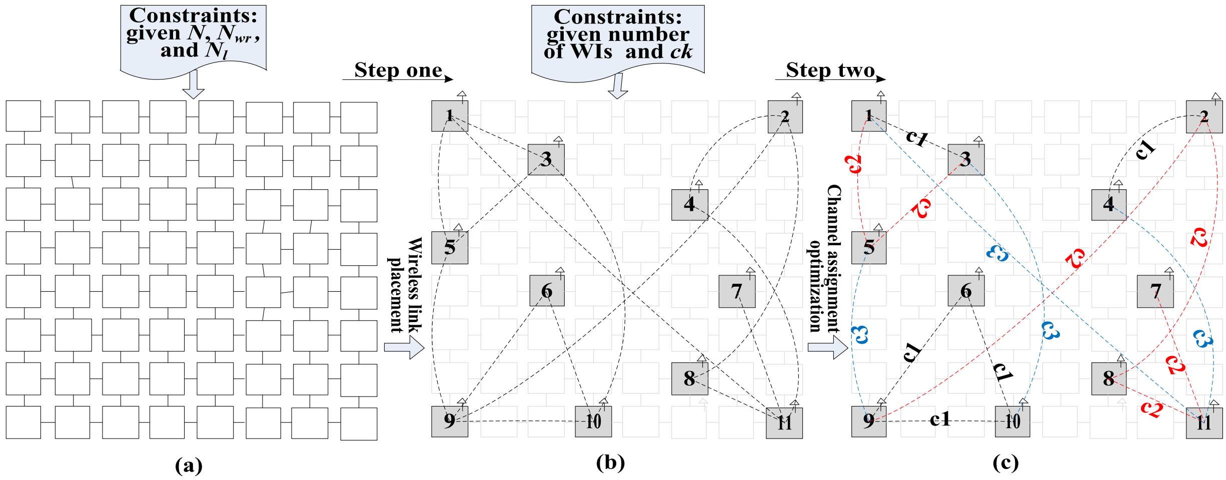


Fig. 2. Issue description of topology generated based channel assignment optimization (a) TCG of wired 2D-Mesh NoC. (b) Wireless topology connection graph. (c) Channel allocation optimization graph.

vertices in V_c if the distance between the two corresponding links $l_{(i,j)}$, $l_{(u,v)}\epsilon E_c$ is within interference range of each other. The distance between two links is defined as the minimum distance between any wireless router node of one link and any wireless router node of the other link. The normalized traffic on a link is defined as the ratio of the link traffic to total network traffic. Fig. 2 shows the issue description of topology generated by channel assignment optimization. Consequently, the topology generation could be divided into two-step process as follows:

Wireless Node and Link Placement: Formally, given a TCG of wired 2D-Mesh NoC as shown in Fig. 2a and routing algorithm, the wireless node and link placement problem are to find a mapping Θ: $(\hat{W}, L)\rightarrow R$ to generate the WTCG as shown in Fig. 2b and minimize the packet average energy $E_{\text{pkt}}(\Theta)$ so that Θ satisfies the available resource constraints. The solution of mapping Θ that is from the set of wireless nodes and set of wireless links to the set of wired router nodes will have a significant effect on communication power consumption of hybrid WiNoC.

Channel Assignment Optimization: Given a WTCG and a set of channels C, the channel assignment optimization is to find a mapping Φ:$L\rightarrow C$(or $V_c\rightarrow C$) to minimize the total network interference $I_{\text{total}}(\Phi)$ of hybrid WiNoC so that Φ satisfies the available channels and SINR constraint. The solution of mapping Φ that from the set of wireless links to the set of channels will have significant effect to improve the network throughput and network interference. The Φ could also be seen as the label on V_c, and $\Phi(a)\epsilon C$ is the channel on which communication link $a\epsilon V_c$ is working. Fig. 2c shows the channel assignment optimization graph(CAOG).

Thus the reasonable and valid wireless link placement and channel assignment under strict constraints are crucial to obtain higher performance gains for the topology design of hybrid WiNoC with large system size.

Since each WR may have multiple WIs including antenna and transceiver, it is reasonable that the different transmission power or transmission range for each WI deployed to WR is assumed here to alleviate co-channel interference. Thus, with different distances between WRs, transmission power of each WI can be adjusted to ensure sufficient power to meet bit-error probability requirement, while not using more power than needed [12]. To describe the interference range and transmission range, the traditional protocol interference model [13,14] is unsuitable in our work due to the assumption of different transmission ranges of WIs deployed to WR in hybrid WiNoC.

Now we assume that the s(i, a) and s$'$(i, a) represent the transmission range and interference range of WI over channel ca assigned to wr_i, respectively. Let s$'$ (i, a) = IRC*s(i, a), where IRC is the interference range coefficient(usually the transmission range and interference range are equal in IEEE 802.11, namely IRC = 1). If a WI over channel ca deployed to WR could transmit to more than one other WR, the actual transmission range s(i, a) of the WI over channel ca is the maximum of the all possible transmission ranges of WI on channel ca. As illustrated in Fig. 3a, it has two possible transmission ranges $d1$ and $d2$ for wireless links $l_{(5,1)}$ and $l_{(5,3)}$ over channel $c2$ for wr_5, respectively. The actual transmission range s(5, 2) is the maximum $d2$ since the $d2$ is bigger than $d1$, and the same to the interference range s$'$(i, a). Fig. 3b illustrates the weighted conflict graph (WCG) over single channel (e.g., $c2$). For instance, the communication link $l_{(3,5)}$ interferes with the links $l_{(1,5)}$, $l_{(2,8)}$, $l_{(2,9)}$ and $l_{(8,11)}$, but not with $l_{(7,11)}$. Thus for vertex $l_{(3,5)}$ numbered 4 in

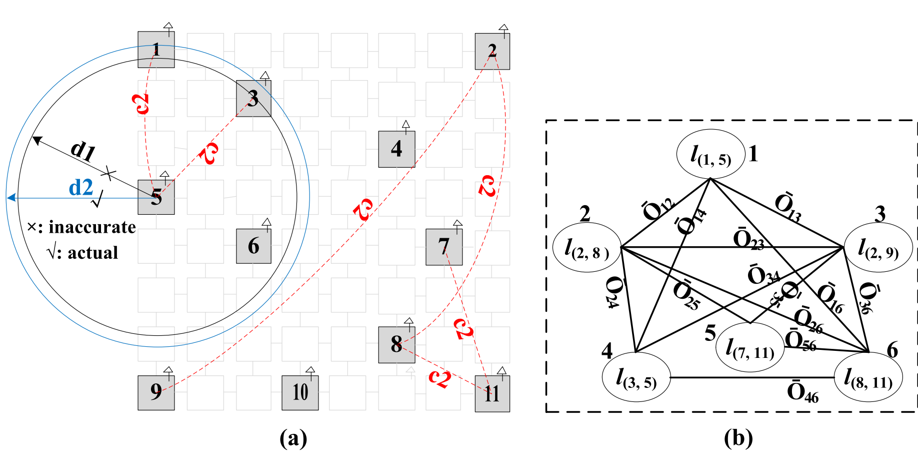


Fig. 3. (a) The actual transmission range. (b) WCG of WTCG over single channel.

Fig. 3b, there are four edges connecting two corresponding vertices in the WCG.

3.2. Power consumption analysis model

The power consumption of system level is the number of power units consumed to transmit all the packets using given routing algorithm for the given topology. For a given WiNoC topology, a unique connectivity matrix $\boldsymbol{\delta}$ is usually used to represent the number of hops [22]. Suppose $\boldsymbol{\delta}_{\text{r-link}}$ and $\boldsymbol{\delta}_{\text{wi-link}}$ are the unique connectivity matrix for the wired links and wireless links in hybrid WiNoC topology, respectively. The average packet energy $E_{\text{pkt}}(\Theta)$ for a given mapping Θ: $(\hat{W}, L) \rightarrow R$ can be defined as follows:

$$E_{\text{pkt}}(\Theta) = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N}[N_{ij}(\boldsymbol{\delta}_{\text{r-link},ij}E_{\text{r-link}} + \boldsymbol{\delta}_{\text{wi-link},ij}E_{\text{wi-link}})]}{\sum_{i=1}^{N}\sum_{j=1}^{N}N_{ij}} \tag{1}$$

where N_{ij} is the communication traffic in packets from source node r_i to destination node r_j. The $\boldsymbol{\delta}_{\text{wi-link}}$ is equal to 0 or 1 due to the single-hop wireless links in the upper-layer network. $E_{\text{r-link}}$ and $E_{\text{wi-link}}$ represent the power consumption consumed by the wired and wireless links through only one-hop, respectively. It is important to note that the value of E_{pkt} equals to the average packet energy going through the pure wired links while there are no packets going through the wireless links in hybrid WiNoC.

3.3. System interference model

The major reason of link interference is that many transmitters work on the same channel simultaneously [14], as a result, the throughput of each wireless link may be decreased dramatically due to the interference from the other link. Let $I(a, b)$ be the interference factor between links $a, b \in V_c$. That is to say, it indicates whether these two links will interfere with each other under channel assignment Φ. According to the WCG, the interference factor is defined in such a way as shown in Fig. 4.

Namely, links a and b do not interfere with each other if two links are assigned different non-overlapping channels even though they are within the interference range of each other. Thus $I(a,b) = \{0,1\}$ and $I(a,b) = I(b,a)$. Besides the interference factor between channels, the link traffic load indicating how busy a link is should be fully considered.

For the two communication links with high traffic load representing more proportion of the busy time, the different channels should be assigned to them to reduce link interference. By contrast, for the two links with low traffic load representing less busy time, they have more probability to be assigned the same channel. Meanwhile, to avoid the overuse of some frequency channels, the traffic balance on every channel is essential to improve network capacity. Thus, the total network interference $I_{\text{total}}(\Phi)$ of overall hybrid WiNoC system for given channel assignment mapping Φ: $V_c \rightarrow C$ can be defined as follows:

$$I_{\textbf{total}}(\Phi) = \sum_{a,b \in V_c} I(a, b)\cdot \overline{O}_{ab} \tag{2}$$

Procedure of Interference factor:

if *links a and b are within the interference range of each other*
    if *the two links are assigned same channel*
        then I(a,b)*=1; //interference with each other*
    else
        then I(a,b)*=0; //no interference*
    end if
else
    then I(a,b)*=0;*
end if

Fig. 4. Procedure of interference factor.

4. Topology generation and overall communication scheme

4.1. Design constraints

As mentioned previously, the topology generation of hybrid WiNoC should be implemented under strict constraints from limited wireless resources(e.g., WRs, WIs, wireless frequency channels etc.). Given the area A_{WI} of single WI [10] and the maximal area overhead $A_{\max}$ in hybrid WiNoC, owing to the constraint that each WR has at least one WI, the total number of WIs $\check{N}$ must satisfy the constraints below:

$$\check{N} = \sum_{i=0}^{N_{wr}-1}\check{R}_i \le A_{\max}/A_{WI} \text{ and } \check{N} \geqslant N_{\text{wr}} \tag{3}$$

Given the total number of WIs $\check{N}$ and the available number of wireless channels k, the total number of wireless links N_l could be deduced as follows:

$$\check{N}/2 \le N_l \le k', \quad k' = C^{2}_{\check{N}-2(k-1)} + k - 1 \tag{4}$$

where k' is the possible maximum number of wireless links while each of the $k-1$ wireless channels has been assigned only one wireless link and all the other $\check{N} - 2(k-1)$ WIs share the remaining one frequency channel.

Given $L(i)$ is the set of wireless links connected to wr_i, the channels assigned to the wr_i should satisfy the channel constraint below:

$$\forall\, \text{wr}_i \in \widehat{W}, \quad \left|\left\{cx \middle| \Phi\left(l_{(i,x)}\right) = cx,\ l_{(i,x)} \in L(i)\right\}\right| \le \check{R}_i \tag{5}$$

Given a matrix A^{NL} indicating the connection relationship between WRs and wireless links, channel assignment matrix A^{LC} indicating the channels assignment to links is defined as follows:

$$A^{NL}_{i,ji} = \begin{cases} 1 & \text{link } l(j, i) \in L \text{ is connected to node wr}_i \\ 0 & \text{otherwise} \end{cases}, \quad A^{LC}_{ji,ca} = \begin{cases} 1 & \text{channel } ca \text{ is assigned to link } l(j, i) \\ 0 & \text{otherwise} \end{cases}$$

Thus the $A^{\text{NC}} = A^{\text{NL}} \times A^{\text{LC}}$ is a channel assignment matrix which represents the channel assignment to wireless nodes. The wireless links satisfy the constraints below:

$$\forall\, l_{(j,i)} \in L, \quad \sum_{i=1}^{N_{wr}} \boldsymbol{A}^{\textbf{NL}}_{i,ji} = 2 \text{ and } \sum_{ca=1}^{k} \boldsymbol{A}^{\textbf{LC}}_{ji,ca} = 1 \tag{6}$$

Although the nodes sharing the same channel that are within the interference range of transmitting node will not send data simultaneously, the interference signal in physical environment due to other ongoing transmissions outside the interference range could still result in the errors of data transmission. Thus the signal to interference and noise ratio (SINR) must be analyzed to ensure the quality of service for supporting low bit error rate (BER) communication. According to the physical model of interference based on SINR [13] and in view of the superimposed effect of interference signal, the wireless router node wr_j could receive data correctly from the sending node wr_i if and only if:

$$SINR_{(i,j)} = \frac{P_i \cdot G'_{(i,j)}}{n_0 + \sum_{wr_u \in WR'_{ij} - \{wr_i\}} I_{(a,b)} \cdot P_u \cdot G'_{(u,j)}} \ge \beta_j \tag{7}$$

where P_i and P_u are the transmitted power of wr_i and wr_u on links $l_{(i,j)}$ and $l_{(u,j)}$, respectively. The $G'_{(i,j)}$ and $G'_{(u,j)}$ represent the transmission gains with relation to communication distance on link $l_{(i,j)}$ and $l_{(u,j)}$. The n_0 is the background noise power around receiving node wr_j. It is the product of noise power spectral density and bandwidth and calculated to be − 63.303 dBm [11] while the bandwidth is set to be 32 GHz. The WR'_{ij} is the set of the other nodes transmitting simultaneously over the same channel with link $l_{(i,j)}$. β_j is the SINR threshold of wr_j.

The on-chip antenna could be classified into two categories: millimeter-wave on-chip antenna operating at GHz frequency and CNTs as optical on-chip antenna operating at THz frequency [23]. Since the omnidirectional antenna allows essentially equal antenna gains for all pairs of wireless transceivers on the chip [11], the omnidirectional millimeter-wave on-chip antenna is used in our work. The transmission gain $G'_{(i,j)}$ of antenna pair is defined as:

$$G'_{(i,j)} = \frac{1}{PL_G} = \left| \frac{\lambda_{sur} \cdot G_d \cdot e^{-\gamma_{sur} d}}{d} + T \cdot \frac{\lambda_{si} G_2 \cdot e^{[-\gamma_{si} \cdot 2d_1/\cos\theta_2]} e^{[-j\beta_{idl} \cdot (2d_2/\cos\theta_3) - j\pi]}}{d'} \right|^2 /(4\pi)^2 \tag{8}$$

where λ_{sur} and λ_{si} are the wavelength of surface wave and silicon substrate, respectively. T is the products of transmission coefficient for each layer according to the literature [23]. It is also shown that the path loss PL_G for wireless multi-path propagation channel in Eq. (8) is introduced by both the antennas and the channel.

4.2. Topology generation based on CAO

Since the locations of wireless nodes and links have significant impact on the channel assignment as the step two in Fig. 2, with regard to two-step process of topology generation, the local optimal WTCG obtaining through step one cannot ensure the optimal solution of channel assignment. Thus, it is important to balance between the objectives of power consumption and network interference. By using the same method in literature [11], the multi-objective optimization design can be converted to single objective optimization. The objective function for power consumption and network interference in hybrid WiNoC is given as:

$$F = \alpha^* E_{pkt}(\Theta) + (1-\alpha)^* I_{total}(\Phi) \tag{9}$$

where α is the importance of two optimal objectives, i.e., $\alpha = 0$ represents an analysis entirely dependent on network interference, namely, it is an interference-oriented optimization (denoted as IOO) to minimize the network interference, but it also causes low-connectivity and high-energy. $\alpha = 1$ represents an analysis entirely dependent on the power consumption, namely, it is an energy-oriented optimization (denoted as EOO) in hybrid WiNoC to go after the highest network connectivity. As mentioned above, the EOO also may cause high interference and low throughput of network. While $\alpha = 0.5$ makes for a balance between power consumption and network interference. The wireless link placement and channel assignment have been shown to be NP-hard [13,14]. With increasing system size, it becomes increasingly difficult to obtain the optimal solution by exhaustive search. Thus, the efficient algorithm that runs reasonably fast and provides best solution is essential to the design of irregular topology in hybrid WiNoC. The Simulated Annealing (SA) has been used in our work to obtain the minimum value of F [24]. Fig. 5 shows the flow diagram of topology generation method based on SA.

Besides using SA algorithm in the external optimization of objective function F for implementing co-optimization between power consumption and network interference, for every solution Θ of wireless node and link placement, the SA is also used in the internal optimal solution Φ of channel assignment while computing the new objective function F_n. Meanwhile, it is important to note that the neighborhood feature of various solutions must be ensured while perturbing the current solution and generating the new solution Θ_n, and thus we usually

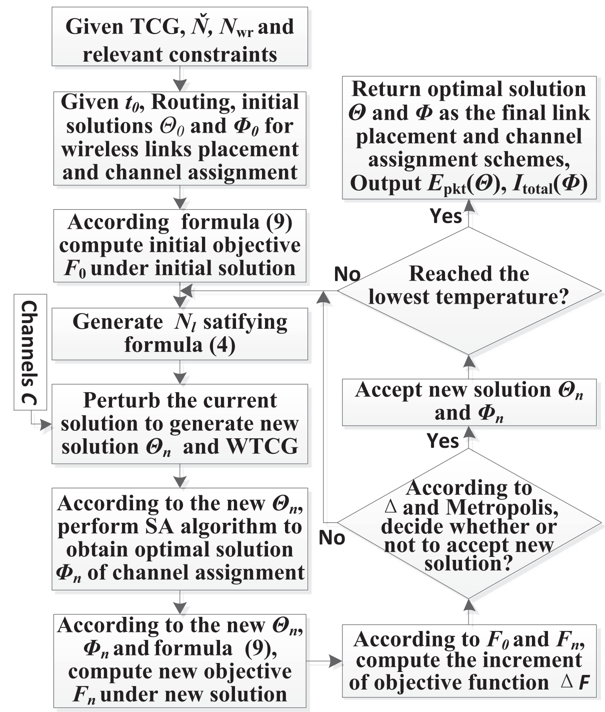


Fig. 5. Flow diagram of topology generation based on SA.

only change the location of one WI or replace one wireless link in the current solution for WTCG.

4.3. Data routing strategy and communication protocols

With regard to the optimal topology WTCG, the data are transmitted via flit-based wormhole routing. It should be noted that the hybrid path may cause deadlocks [3,8]. Thus the dimension order routing XY is used to avoid the deadlock in the lower-layer wired 2D-Mesh network. We use South-East [11,25] routing algorithm for the wireless links to guarantee a deadlock-free path in the irregular wireless network. The data routing strategy for irregular hybrid WiNoC is shown in Fig. 6.

The routing strategy first finds the nearest wireless nodes wr_i and wr_j to wired nodes r_i and r_j, respectively. Then it checks whether there exists a wireless link between wireless nodes wr_i and wr_j. If there is no such wireless link, the data follow the XY routing algorithm until it reaches the destination. Otherwise, the algorithm compute the transmission hop count from r_i to r_j while wireless links are used. If it can save hop count by taking wireless link, the wireless link is selected and the South-East routing algorithm is used to guarantee that there is no deadlock. Otherwise, the pure wired links and XY routing are used.

Under these conditions of multiple WRs sharing the same channel and transferring data concurrently, to handle the channel contention and interference, a low-overhead arbitration mechanism needs to be designed to enable a particular WI of WR to use the particular wireless frequency channel. In the previous work, a token passing protocol [11,12] is used to select which transceiver will use the wireless channel at any particular time, thereby removing the possibility of channel contention. The distributed token passing protocol that is fair in sharing the medium has been adopted to avoid the need for a centralized control and synchronization mechanism [11,12]. For the hybrid WiNoC topology based on the token passing protocol, possession of the token represents the right to transmit, thus there will be only one WI working on particular frequency channel to transmit data at any particular time. However, since there may be multiple wireless links sharing the same channel and transferring data concurrently to improve the frequency channel utilization, the token passing mechanism is unsuitable and

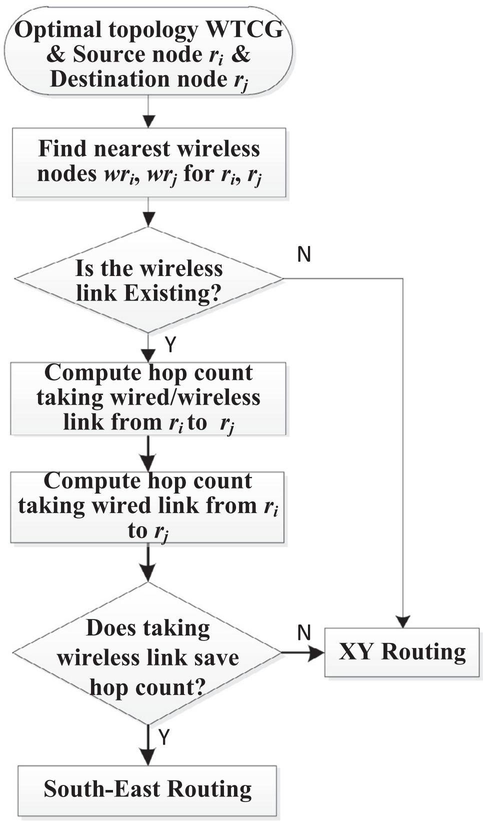


Fig. 6. The data routing strategy for irregular hybrid WiNoC.

inefficient for the topology generated by using CAO in hybrid WiNoC with large system size. To address these issues, by taking full advantage of the inherent broadcast characteristic of wireless links, we have proposed a new centralized control mechanism as the MAC protocol that is suitable for our hybrid WiNoC to improve the communication performance.

As shown in Fig. 7, an efficient channel centralized controller unit (CCCU) that was deployed a single WI with transceivers of all frequency channels is placed at the top of the optimal topology. This facilitates the exchange of control signals between the CCCU and WIs assigned to WRs by using wireless links. According to the gateway design in mWNoC [11], it is feasible to implement one WI that has all three channels assigned to it. The CCCU is in charge of maintaining several lookup tables for external token control word (ETCW-LUTs) and granting the wireless channel access to one or multiple particular WIs at a given instant of time.

Aiming at fairness and maximal communication parallelism of accessing wireless channel, the pseudo code for the setup process of

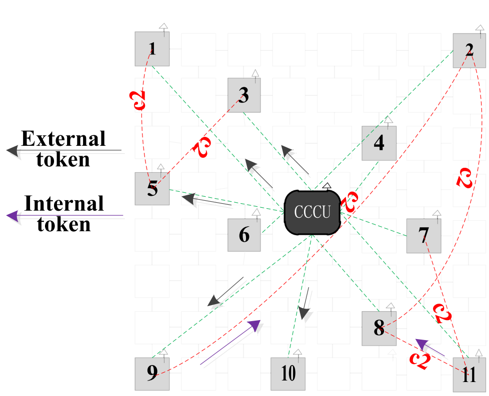


Fig. 7. Proposed CCCU by broadcasting transmission and two-level wireless token.

Table 1
An example of ETCW-LUT for channel $c2$.

	$l_{(1,5)}$	$l_{(2,8)}$	$l_{(2,9)}$	$l_{(3,5)}$	$l_{(7,11)}$	$l_{(8,11)}$	CW	Holding time
1	1	0	0	0	1	0	0 × 22	T_{th}
2	0	1	0	0	0	0	0 × 10	T_{th}
3	0	0	1	0	0	0	0 × 08	T_{th}
4	0	0	0	1	1	0	0 × 06	T_{th}
5	0	0	0	0	0	1	0 × 01	T_{th}

ETCW-LUT based on WCG is shown in Algorithm 1.

Since the setup process of ETCW-LUT separately existing for every channel in the CCCU is implemented off-line, there is no hardware overhead associated with this algorithm on the chip except the data maintaining of ETCW-LUTs, e.g., the ETCW-LUT for channel $c2$ with five command words (i.e., 0 × 22, 0 × 10, 0 × 08, 0 × 06 and 0 × 01) as listed in Table 1.

The CCCU will periodically broadcast a control packet including CW from the ETCW-LUT for a channel to all the WIs over the same channel in a specific circular order. The data T_{th} representing the token-holding time just need to be broadcast only once at the initial stage. Whether the WIs of a wireless link can use the channel to send data depends on the corresponding bit value of CW received from the CCCU. The two WIs of every wireless link with corresponding bit equaling to value 1 in CW could use the channel. The simultaneously transmitting from the two WIs of every wireless link may lead to data collision. To address this issue, an internal token for every wireless link is set to grant the wireless channel access to one of the two WIs of the link. In order to avoid starvation, each internal token is passed between the two WIs in a round robin fashion along the corresponding wireless link through the wireless channel similar to data. Namely, a two-level wireless token arbitration scheme that granting the channel access to a wireless link and to a WI of the wireless link is used in our communication protocols as shown in Fig. 7. The WI simultaneously possessing the external token indicated by CW from CCCU and the internal token of the link connecting the WI at some time instant can send or receive data over the corresponding channel. The authorizing of access to wireless links has a shorter token returning period from external token than directly to the wireless nodes obviously.

In addition, each WI will be equipped with a counter to store the T_{th} receiving from CCCU. The counter in WI immediately starts to count down after the WI receives the T_{th} from CCCU. The WI simultaneously possessing the two-level token will immediately transmit the flits until the T_{th} is up. When a WI does not have the two-level token, the data is stored in a buffer of WR until the two-level token is received. If no data needs to be transmitted for a WI, it will pass the internal token to the other WI of the wireless link. If the two WIs of a wireless link have no data to be transmitted, an ACK signal for external token from one of the two WIs will be send to CCCU, so that the CCCU can broadcast a new control packet including the next new CW for a channel and T_{th} to all the WIs timely after it has received the ACK. However, it is not always suitable to send an ACK signal to the CCCU. The ACK signal probably will not reach the CCCU because the CCCU is beyond the transmitting range of a WI or it has more than two WIs from many wireless links and sends the ACK signal to CCCU simultaneously, i.e., the ACK signal from the WIs of $l_{(1,5)}$ will not reach the CCCU. Thus, whether the WI could send ACK signal successfully should be carefully planned in the topology implement. For example, The WIs of a wireless link could send the ACK signal while only one wireless link is granted the channel access. Although some studies have proposed run-time tunable transmitting power based on the required destination [26] to change the transmitting range, it increase the design complexity and latency. In these cases, the CCCU will not receive the ACK signal. If the CCCU do not receive ACK signal from the WI successfully, it will wait to broadcast a new control packet until the T_{th} is up. This case does not happen very often due to the sharing scheme of transmitters between two WIs, however, the idle time that no data to be sent can still be reduced by using a small T_{th}. The failure of the token passing mechanism such as token loss or disability in transmission [27] could be alleviated by using channel centralized controller unit.

The CCCU is placed at the center of the topology. The longest communication link from the CCCU to a WR is shorter than 15 mm for a 20 mm × 20 mm die. The speed of electromagnetic wave was extracted in [28] and found to be 0.95×10^8 m/s in silicon dioxide. Therefore, the transmission latency of wireless link is computed to be about 158 ps and hence the signals can be transmitted within a single wired clock cycle for a communication range of 15 mm. The reconfiguration window has been discussed in [30], and the period of reconfiguration window is set to be 180 cycles by the simulation in our work. The latency of reconfiguration is about 2–4 wired clock cycles depending on different core-system sizes at 16 Gbps data rate. Additionally, the CW could be prepared in advance at the same time as the transmission of the previous data flit, thus the reading latency of CW from CCCU is negligible. The latency arising from the CCCU and from wireless link to a WR for the transmission of CW is only one clock cycle. The centralized control mechanism is non-scalable. Since the placement of wireless link and channel assignment fully depend on the traffic characteristics, it is important to note that the optimal topology generated by the CAO is suitable for the design of application-specific wireless NoC with known traffic characteristics. The optimal topology based on CAO and CCCU including ETCW-LUTs have to be regenerated for different specific applications.

5. Experimental results and analyses

To verify the method of topology generation and performance enhancement based on CAO in hybrid WiNoC, a system level simulation architecture has been developed by modifying the cycle accurate simulator Noxim and embedding the model information for optimal topology WTCG, location information of wireless nodes and links placement as shown in Fig. 8. To guarantee a low bit error rate (BER), the transmitting node must maintain certain transmitting power.

To evaluate the additional power consumption and area of the circuits implementing the channel arbitration, the digital part of CCCU (exclusive of the WI) used for maintaining several ETCW-LUTs and sending control packet of wireless channel access as shown in Fig. 7 has been synthesized by using Synopsys Design Compiler and 90 nm CMOS technology. Meanwhile, the power consumption and area of wired or

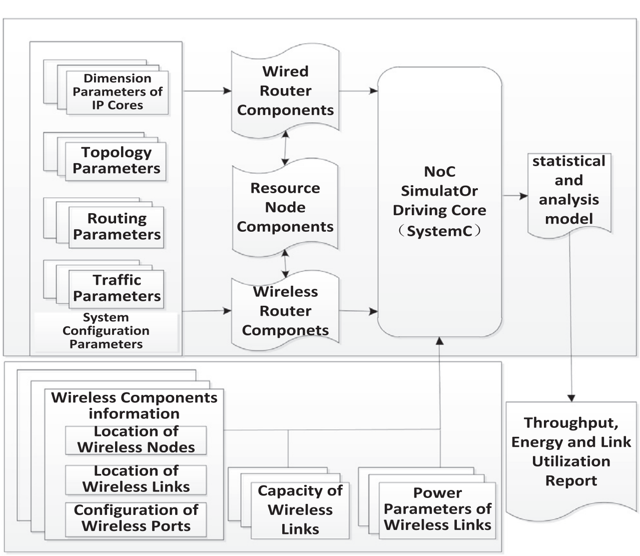


Fig. 8. System level simulation architecture for hybrid WiNoC.

wireless routers were estimated using Orion 2.0 simulator in 45 nm [29] as shown in Table 2 below. In this work, the routers all have 2 VCs per port, each virtual channel has 8 buffers, and each data path is considered to be 32-bit wide. The load parameter used in Orion is set to be 1.0.

In the previous work, it has been shown that it is enough to support a data rate of at least 16 Gbps, and a BER < 10^{-9}(even lower than 10^{-15}) with a given SINR level using an OOK (On–Off Keying) modulation scheme for a communication range of 20 mm [11,12]. The power consumption of one-hop wireless link is the sum of the energy consumed by the WR(exclusive of WIs), the WI as shown in Table 2 and the transmitted power P_i. The transmitted power consumption P_i (dBm) can be calculated as $P_i = \text{SINR} + N_{floor} - G'_{(i,j)}$, where the N_{floor} in dBm is the receiver noise floor and computed to be − 55.5 dBm [11]. High resistivity silicon substrate (ρ = 5kΩ cm) is used in hybrid WiNoC. The transmission gain $G'_{(i,j)}$ was computed to be about − 32 dB and − 9 dB for the communication range of 20 mm and 1 mm according to Eq. (8), respectively. For a 20 mm × 20 mm die, supposing the SINR threshold $\beta_j = 28.5$ dB at receiving node to ensure the BER performance of 10^{-9} using an OOK modulation scheme [11], the transmitting power P_i must be bigger than 5 dBm or 3.16 mW for a communication range of 20 mm [11] and a data rate of 16 Gbps. The energy dissipations are 1.594 pJ/bit [27] for 5 mm metallic wire. According to Table 2, the power consumption of one-hop wireless link of 20 mm is calculated to be 3.056 pJ/bit (inclusive of 8*8 WR and WI). However, the power consumption for one hop wired link of 5 mm is about 2.073 pJ/bit. Since the WR will also consume more energy arising from the more input/output ports than the pure wired router as shown in Table 2, the one-hop wireless transmission will consume more energy than the one-hop wired interconnect actually. The insertion of wireless link benefits from the decreasing of hop count for data communication. It should be noted that the trends are moving towards wireless transceivers with the data rates near 32 Gbps and energies near 1 pJ/bit as illustrated in [12] and [30]. Thus, it will further decrease the power consumption by the insertion of wireless link.

To obtain the optimal topology generated by EOO method, using the application-specification distribution FFT as an example as shown in Table 3 below, the optimal number of WIs $\check{N}$ is found to be 38, 69 and 110 for three different WiNoC sizes(i.e. N = 144, 324 or 576) by performing SA algorithm as used in [3] and [11], respectively. The optimal number of WIs $\check{N}$ in CAO (or SFC−OO, MOWI, etc.) is the same as in the EOO method for the fair comparison of different design methods above. Thus, the fair comparison for different design methods (e.g. MOWI, SFC−OO, etc.) must be implemented under the same resource constraints (i.e. $\check{N}$ and k). We use the topology generation algorithm as shown in Fig. 5 to find the optimal topology based on channel assignment optimization scheme. The fast Cauchy annealing is used as the cooling schedule. The execution results under uniform traffic for 144 core-system hybrid WiNoC is shown in Fig. 9. It can be seen that the objective function F for power consumption and network interference decreases gradually with iteration count and finally converges.

The list of configuration parameters for CAO method such as the values of N_b, N_{wr} and number of wireless links N_l as shown in Table 3 was obtained by using the topology generation algorithm based on SA as shown in Fig. 5.

During simulation, the wired links are driven with a clock of frequency 1 GHz, and the bandwidth of wireless channel is set to be 16 GHz, corresponding to a bit rate of 16 Gbps under OOK modulation. In this work, we assume a flit width of 32 bits. Hence, to send the whole flit, it will need 32 time slots to transmit a flit. The input and output ports have two virtual channels, each having a buffer depth of 8 flits. The simulation time was set at 160,000 wired clocks. The data of traffic patterns was introduced by the traffic generator in the modified system level simulator above. The average hop count and packet average energy for a 144 core-system with 3 wireless channels in hybrid WiNoC are shown in Fig. 10. To the Fast Fourier Transform (FFT) as a

Table 2
The power consumption and area of CCCU and other components.

Components	Area (mm^2)	Power consumption (mW)	Data rate (Gbps)	Energy (pJ/bit)
5 × 5 router	0.0834	76.623	1	0.479
8 × 8 WR (exclusive of WIs)	0.1965	142.235	1	0.556
6 × 6 WR (exclusive of WIs)	0.1158	97.155	1	0.506
WI	0.32[11]	36.7 [11]	16	2.3
CCCU	0.0681	1.341	16	0.0838

Table 3
Parameters setting for cycle accurate simulator in system level.

Parameter	Setting	Parameter	Setting
Technology	45/90 nm	Number of virtual channels	2 VCs
Wired clock frequency	1 GHz	$\check{N}$ (FFT)	38, 69, 110
Bandwidth of wireless channel	16 GHz	N_l (FFT)	92, 124, 187
Number of IP cores N	144,324,576	N_{wr} (FFT)	16, 37, 59
Number of wireless channels k	3 [11]	SINR threshold β_j	28.5 dB

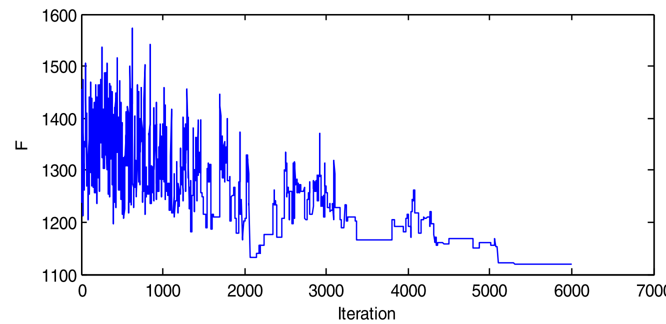


Fig. 9. Execution results of total objective function *F* based on the SA algorithm.

Algorithm 1
Setup process of ETCW-LUT based on WCG.

Step 1: According to the WCG of channel *ca* as shown in Fig. 3b, we create a collection $L'(ca)$ including all wireless links sharing the same channel *ca*, and $|L'(ca)|=N'_l$. For instance, $L'(c2)=\{l_{(1,5)}, l_{(2,8)}, l_{(2,9)}, l_{(3,5)}, l_{(7,11)}, l_{(8,11)}\}$. Then a flag variable *FLAG* with initial value *FALSE* for every wireless link in $L'(ca)$ is set. Every *FLAG* represents whether the wireless link has been granted previously to use the channel *ca* for transferring data or not. Namely, *FLAG* = *FALSE* represents that the wireless link has not previously been granted to use the channel *ca*.

Step 2: To ensure the fairness of channel contention, select a wireless link from $L'(ca)$ sequentially and then do the following steps:

Step 2a: If the flag *FLAG* of the selected wireless link is *TRUE,* do nothing and select the next wireless link in sequence from $L'(ca)$ to ensure the fair use of channel, and go to Step 2a; otherwise if the flag *FLAG* of the selected wireless link is *FALSE,* we create a new command word (CW) including N'_l bits and set a initial value 0 for every bit. Namely, CW = $(b(0),b(1),...b(N'_l-1))$, where the bit $b(0)$ corresponds to the first link(e.g., $l_{(1,5)}$) in $L'(ca)$, and the bit $b(1)$ corresponds to the second link (e.g., $l_{(2,8)}$) in $L'(ca)$ and so on. The value 1 or 0 for the bit $b(i)$ in $L'(ca)$ represents whether the corresponding *i*th wireless link possesses the wireless token to use the wireless channel *ca* for data transmission or not.

Step 2b: Set the corresponding bit $b(i)$ for the selected wireless link to 1 in CW, and set the corresponding flag *FLAG* of the selected wireless link to *TRUE*.

Step 2c: Search all the wireless links without interference with the selected wireless link in the WCG, and then put all the searched wireless links into a new collection *S*. Although all the searched wireless links in collection *S* do not interfere with the previously selected wireless link, the searched wireless links in collection *S* may interfere with each other. If collection *S* is empty, then go to Step 2e; otherwise if *S* is nonempty, aiming at maximal communication parallelism of accessing the wireless channel *ca*, create several maximal subsets $s(1)$, $s(2)$,..., $s(n)\epsilon S$(i.e. $s(1)\cup s(2)\cup,..., \cup s(n)=S$) and guarantee that all the wireless links in one maximal subsets $s(i)$ do not interfere with each other.

Step 2d: In order to minimize the wireless token waiting time of wireless link from last access to channel and obtain the maximal communication parallelism, a subset $s(i)$ including a wireless link with flag value of *FALSE* or having the maximal number of wireless links will be selected preferentially to use the wireless channel *ca*. Then the corresponding bits of all the wireless links in subset $s(i)$ selected preferentially will also be set to 1 in CW, meanwhile, the corresponding flag *FLAG* of the wireless link in subset $s(i)$ is set to *TRUE*.

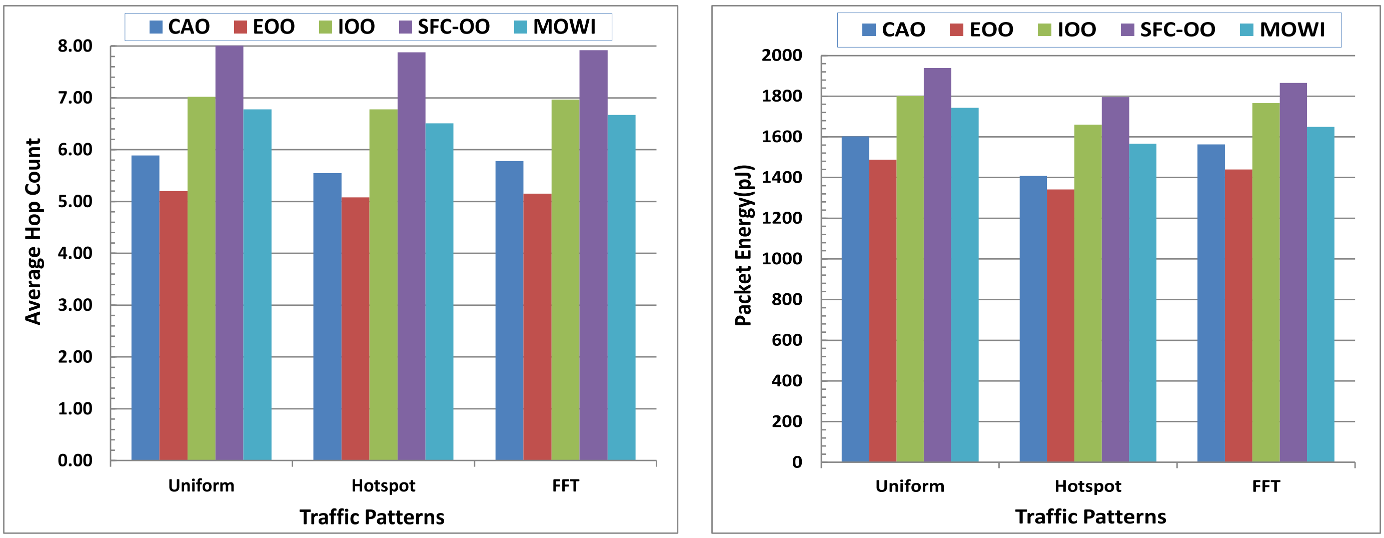
Step 2e: Put the newly generated CW into the ETCW-LUT and select the next wireless link in sequence from $L'(ca)$; then go to Step 2a until the corresponding bits of all the wireless links in $L'(ca)$ are *TRUE*.

benchmark, a 512-point FFT (or 1024-point FFT) was considered on the same 128 (or 256) process elements (PEs), wherein each PE performs a 4-point radix-2 FFT computation. We can see from Fig. 10(a) that the topology generated by EOO without the consideration of network interference has the shortest average communication distance than the topologies generated by the other design methods. Although the average hop counts of topology generated by CAO is slightly higher than that of the topology generated by EOO, it is significantly lower than that of the toplogies generated by the other methods (i.e., IOO, SFC−OO and MOWI).

The packet average energy is collected based on the analysis model of introduced power consumption and performed under various network scenarios. Fig. 10(b) depicts packet average energy comparison for 144 core-system under different traffic patterns using the five different topology design methods in hybrid WiNoC with three channels. Although the packet energy of topology generated by CAO is slightly higher than that of the topology generated by EOO which has the highest network connectivity, the topology generated by CAO has a packet energy saving of about 5.18%∼16.20% than the topologies generated by MOWI and SFC−OO respectively in hybrid WiNoC of 144 core-system.

Fig. 11 shows the throughput and average latency plots as a function of traffic injection load among different optimal methods and constraints under the uniform traffic profile. Network saturation throughput is defined as the point where throughput no longer grows with injection load [19], which is defined as the number of flits injected by each node per cycle, and average latency is the average time in cycles a packet takes to reach the destination. The overall performance trends of all five WiNoC using different optimal methods are similar. The network throughput increases with the injection load, and after a saturation point, the throughput stops increasing.

It can be concluded from Fig. 11(a) that the topology generated by CAO have better throughput than the topologies generated by other optimal methods. For a 144 core-system, the topology generated by CAO saturates at an injection load of about 0.30, with saturation throughput of 0.199. The topologies generated by SFC−OO and MOWI saturate at an earlier injection load of about 0.2 and 0.25, with saturation throughputs of 0.110 and 0.167 respectively. The topology generated by SFC−OO has the lowest throughput due to the less wireless links under the limitation of a single-frequency channel used only once. The topology generated by MOWI has moderate throughput since the distribution of WIs is not the optimal condition. Regarding average latency as can be seen from Fig. 11(b), because the topology generated by CAO makes efficient use of wireless channels and parallelism, the average communication latency of topology generated by CAO is reduced about 12.93%–24.04% compared to that of the topologies generated by MOWI and EOO. Moreover, while the network is in a saturation situation, the average communication latency will rise sharply caused by network congestion.



(a) Average hop count comparison (b) Packet average energy comparison

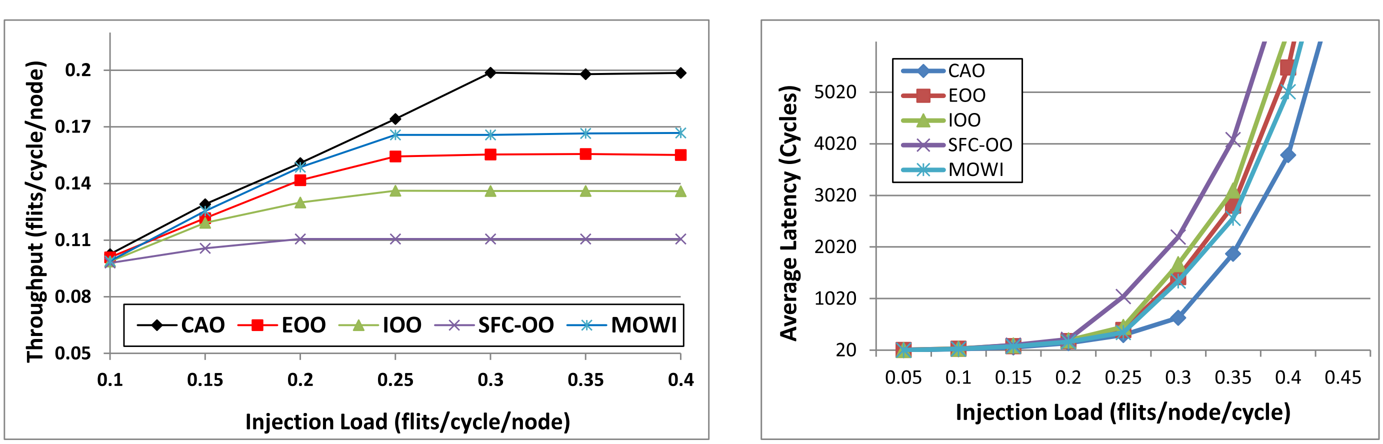
Fig. 10. Average hop count and packet average energy for a 144 core-system.

To further verify the performance of topologies with larger scale generated by various topology generation methods, a performance analysis for larger scales in 324 and 576 core-system was done as shown in Figs. 12–14. The comparison of average hop count and the comparison of packet average energy under different traffic patterns in 324 and 576 core-system hybrid WiNoC are shown in Figs. 12 and 13, respectively. It is clear that the packet energy of topology generated by CAO is lower than that generated by the other design methods except for by EOO. Furthermore, the average packet energy of topology generated by CAO will get closer to that of the topology generated by EOO with the gradually increasing sysytem size.

Figs. 14 and 15 depict respectively the performance analysis of throughput characteristic and average latency for 324 or 576 core-system under hotspot and FFT traffic patterns in hybrid WiNoC. It can be seen that the topology generated by CAO has more throughput than topologies generated by the other design methods in hybrid WiNoC. Since the optimal topology generated by CAO could achieve more parallel communication links, it has the higher saturation throughput than the topologies generated by the other design methods. Owing to the lower network connectivity arising from minimizing network interference or limited wireless channels, and thus the saturation throughput and parallelism of topology generated by IOO and SFC–OO will also degrade accordingly. The average latency of topology generated by CAO is also better than the other optimal topologies as can be seen in Fig. 15. We observed that all of these latencies are reduced in WiNoC topology generated by CAO for different injection loads.

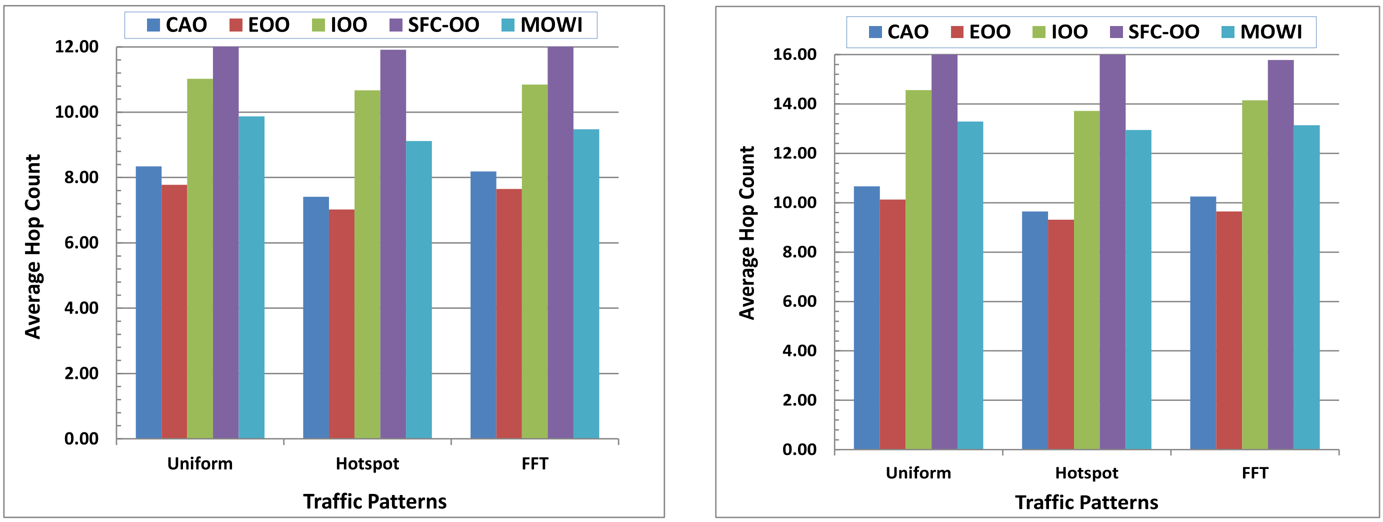
The comparison of average utilization of frequency channel for different core-system sizes under uniform pattern in hybrid WiNoC is shown in Fig. 16. The frequency channel utilization is defined as the ratio of the sum of all the link traffic sharing the frequency channel to channel bandwidth in a time interval. The topology generated by CAO has 15.29%–30.85% higher frequency channel utilization than the topologies generated by MOWI and EOO. It is clear that using wireless frequency reuse effectively improves the channel utilization due to the more parallel wireless links over the frequency channels. Hybrid networks of greater dimension benefit more from parallel transmission links and frequency reuse. It can be concluded from the figures above that the topology generated by CAO outperforms the topologies generated by the other design methods in terms of achievable power efficiency, throughput and latency.

The area for 5×5 router and 8×8 WR (exclusive of WIs) were estimated using Orion 2.0 in 45 nm technology. As listed in Table 2, the area of 8×8 WR is 0.1987 mm^2 (where 0.0209 m^2 for buffer, 0.1593 mm^2 for crossbar). The area of CCCU including WI is about



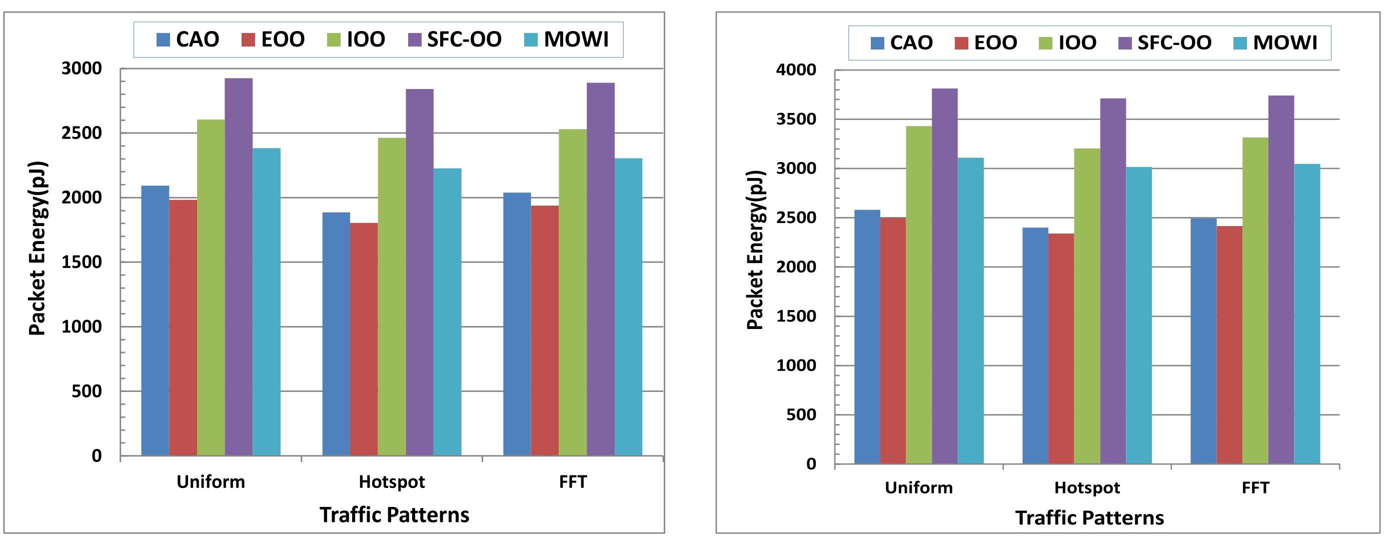
(a) Throughput characteristic (b) Average latency comparison

Fig. 11. Throughput and average latency under uniform traffic for a 144 core-system.



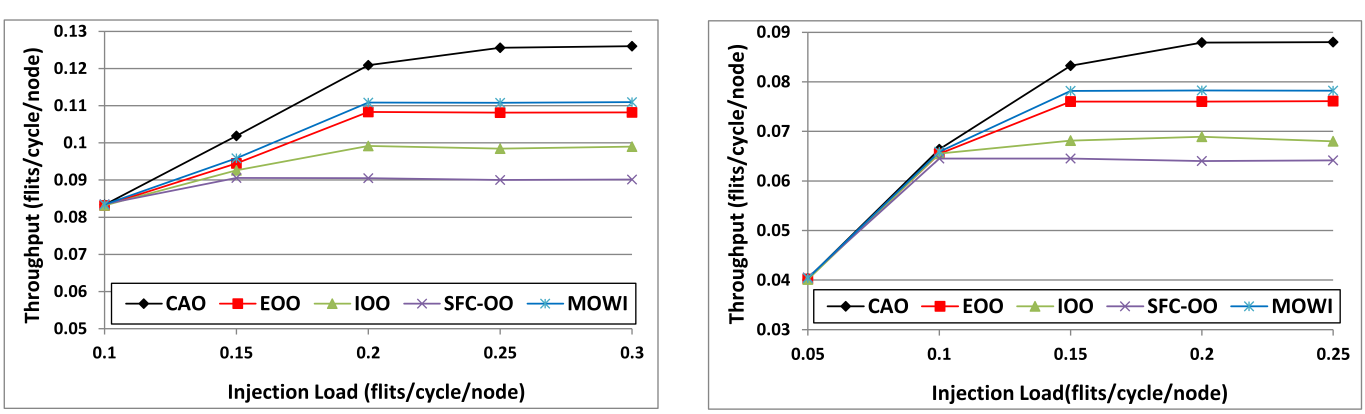
(a) Average hop count for a 324 core-system (b) Average hop count for a 576 core-system

Fig. 12. Performance analysis of average hop count.



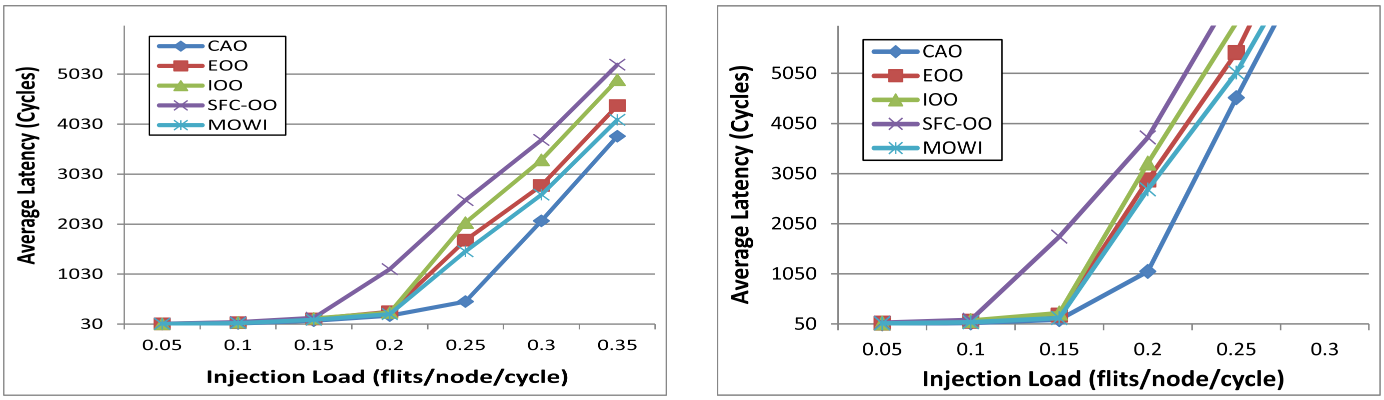
(a) Average energy for a 324 core-system (b) Average energy for a 576 core-system

Fig. 13. Performance analysis of packet average energy.



(a) Throughput for a 324 core-system under hotspot (b) Throughput for a 576 core-system under FFT

Fig. 14. Performance analysis of throughput characteristic.



(a) Latency for a 324 core-system under hotspot (b) Latency for a 576 core-system under FFT

Fig. 15. Performance analysis of average latency.

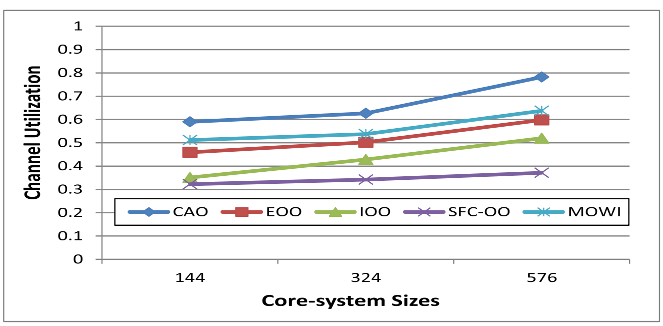


Fig. 16. Average channel utilization for different core-system sizes.

0.3881 mm^2. So it can be seen that the wireless links will increase the area in hybrid WiNoC, but for the 400 mm^2 die, the additional area overhead of CCCU (about 0.0681 mm^2) is negligible. On the one hand, the topology generated by CAO has higher gain in terms of throughput, latency and power consumption at the cost of little area overhead. On the other hand, the proposed topology generation method advances the communication parallelism under limited wireless resources.

6. Conclusions

In this work, we proposed an topology generation based on channel assignment optimization(CAO) for hybrid WiNoC with large system size, and the communication protocols based on weight conflict graph were designed accordingly. The CAO method has strived to reduce the total network interference while decreasing power consumption. Meanwhile, the optimal method has improved the throughput by properly increasing wireless links under sufficient SINR. The experimental simulation has demonstrated that the optimal topology generated by CAO outperforms the conventional counterparts in terms of achievable throughput, power-efficient, latency and frequency channel utilization. Especially, the lager the core-system size is, the more obvious performance enhancement is obtained. In ongoing and future investigations, we intend to further investigate the performance gain by using multiple partially overlapping channels in hybrid WiNoC. Additional, the MAC mechanism based on centralized control can negatively affect the scalability, thus a MAC mechanism based on distributed control is our ongoing work due to its better scalability and distributed decision making nature.

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Jianhua Li was born in Hubei, China, in 1980. He received the B.S. and M.S. degrees from Northeast Dianli University, Jilin, China, in 2004 and 2007, respectively. He is currently working in Institute of Computer Application, Taizhou University, Taizhou, China, and pursuing the Ph.D. degree in communication and information systems with the Department of Electronic Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China. His current research interests include Network-on-chip, design of system-on-chip, high performance computer architecture, and application-specified integrated circuit design.

Han Li was born in Henan, China, in 1980. She received the M.S. degree from Northeast Dianli University, Jilin, China, in 2007. She is currently a lab technician with the Department of Computer, Taizhou University, Taizhou, China. Her current research interests include application of computer network and multiprocessor systems.

Yongliang Hu was born in Zhejiang, China, in 1973. He received the M.S. degree from Hangzhou Dianzi University, Hangzhou, China, in 2003. He is currently an associate professor with the Institute of Computer Application, Taizhou University, Taizhou, China. His current research interests include application of computer network and network-on-chip.

Gaobiao Wu was born in Zhejiang, China, in 1970. He received the B.S. and M.S degree from Zhejiang University of Science and Technology and Hangzhou Dianzi University, Hangzhou, China, in 1995 and 2004, respectively. He is currently a lecturer with the Institute of Computer Application, Taizhou University, Taizhou, China. His current research interests include embedded systems and electronic system integration.