Onyx: A new heuristic bandwidth-constrained mapping of cores onto tile-based Network on Chip

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Abstract: Due to the ever-increasing complexity of System on Chip (SoC) design, and non-efficiency of electric bus to exchange data between IP cores in Giga scale, the Network on Chip (NoC) is presented with more flexible, scalable and reliable infra-structure. As mapping of IP cores on a given platform is one of three aspects of NoC design, with the focus on tile-based NoC architecture, we have introduced a heuristic method for mapping cores on mesh platform. Onyx¹ algorithm is a method with less complexity, and it minimizes hop count between IP cores, leading to improving energy consumption and other performance parameters. We have used this method with two real applications, i.e. VOPD², and MPEG-4 and compared it with some existing algorithms. The results show that our developed method is more efficient.

Keywords: Network on Chip, topology, mapping, core graph, NoC architecture graph, communication cost, bandwidth constraints

Classification: Integrated circuits

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1 Introduction

The network on chip is a novel approach to overcome the constraints of SoC, and to establish inter-chip communication based on data communication network [1]. One of the influencing factors in energy consumption, latency and other performance parameters of NoC is topology. In this research, the mesh topology is selected as the platform for mapping cores due to its more flexibility as far as scalability and implementation are concerned. In this platform, each core is linked to a router by a resource network interface (RNI). Different mapping algorithms are presented to decide which core should be linked to which router. Considering the importance of mapping in NoC as one of three aspects of NoC design [2], in this article we attempt to present a heuristic mapping model that could map cores on the mesh platform automatically.

2 Related Works

The current researches mostly focus on mapping techniques for NoC platforms with two dimension mesh topology. The NMAP method that runs mapping with regard to bandwidth constraints and minimizing communication delay is selected as the criterion in most projects, and is highly efficient as far as communication cost is considered [3]. In [4] a binomial mapping method is introduced. The latter comes along with an optimal algorithm aiming at minimizing total traffic on network, the number of hops, and hardware costs. The Branch-and-Bound algorithm, presented in [5] has been able to map IP cores on tile-based NoC architecture, and it has tried to minimize total energy consumption, and to overcome bandwidth constraints. Also, the mapping of clusters onto the physical topology of processors has been studied in the field of parallel processing. In [6], PMAP, a two-phase mapping algorithm for placing clusters onto processors is presented. In this field, the mappings produced by the PMAP algorithm are shown to have lower communication costs than mappings with previous algorithms.

3 Mathematical Formulation of Mapping

Each application is divided to several IP cores. The manner of relation

between cores is shown by a core graph.

Definition1: The core graph is a directional graph $G(V, E)$, whose each vertex $v_i \in V$ shows a core, and a directional edge $e_{i,j} \in E$ illustrates connection between v_i and v_j . The weight of $e_{i,j}$ that is shown as $comm_{i,j}$, represents the bandwidth requirement of the communication from v_i to v_j .

We display an IP core along with a router connected to it by a RNI as a tile, and the manner of tiles' link and bandwidth between tiles would be determined by NoC architecture graph.

Definition2: The NoC architecture graph is a directional graph $A(T, L)$ whose each vertex $t_i \in T$ represents a tile in the NoC architecture, and its directional edge that is shown by $l_{i,j} \in L$ shows a physical link from t_i to t_j and for each $l_{i,j}$ a $BW(l_{i,j})$ is considered. In this paper, tiles are connected to each other through a mesh interconnection. We have employed x-y routing algorithm and $r_{i,j}$ shows routing path between t_i and t_j . Each $r_{i,j}$ includes a number of links out of existing links in NoC architecture, and these links are defined with $L(r_{i,j})$. The definitions are presented in Fig. 1-a.

Fig. 1. (a) Mapping of VOPD core graph on NoC Architecture graph, (b) Mapping of MPEG-4 core graph on NoC Architecture graph

The core graph mapping $G(V, E)$ on NoC architecture graph $A(T, L)$ is defined by a one to one mapping function.

$$\text{map} : V \rightarrow T, \text{ s.t. } \text{map}(v_i) = t_j, \forall v_i \in V, \exists t_j \in T, |V| \leq |T| \quad (1)$$

In core graph each edge is treated as a flow of single commodity, repre-

sented as d^k and its amount which indicates the required bandwidth for each edge is displayed with $vl(d^k)$. The set of all commodities represented as D is achieved as follows:

$$D = \left\{ d^k : vl(d^k) = comm_{i,j}, k = 1, 2, \dots, |E|, \forall e_{i,j} \in E, \right. \\ \left. \text{with source}(d^k) = \text{map}(v_i), \text{dest}(d^k) = \text{map}(v_j) \right\} \quad (2)$$

The BW constraints are displayed using by inequality:

$$\forall link l_{n,m}, \sum_{k=1}^{|E|} vl(d^k) \times f(l_{n,m}, r_{\text{source}(d^k), \text{dest}(d^k)}) \leq BW(l_{n,m}) \quad (3)$$

$$f(l_{n,m}, r_{i,j}) = \begin{cases} 1, & \text{if } l_{n,m} \in L(r_{i,j}) \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

Considering the above-mentioned issues, it can be stated that a proper mapping should overcome bandwidth constraints, and improve the energy consumption and other performance parameters too. To calculate energy consumption a model is introduced in [7]. This formula is designed based on energy for sending one bit on communication channel from node i to node j in mesh topology, as illustrated in Formula 5. $E_{bit}^{ti,tj}$ indicates energy consumption of transmission of one bit between two tiles. E_{Rbit} and E_{lbit} display energy consumption to forward one bit in router and link respectively. n_{hops} is the number of routers that one bit has to pass to be sent from the source tile to the destination one. And finally energy consumption for transmitted data could be displayed by Formula 6:

$$E_{bit}^{ti,tj} = \sum_{k=1}^{n_{hops}} E_{Rkbit} + (n_{hops} - 1) \times E_{lbit} \quad (5)$$

$$E_{total}^{ti,tj} = \text{Data size} \times E_{bit}^{ti,tj} \quad (6)$$

As illustrated above, one significant approach to lessen energy consumption is to limit n_{hops} between related cores in core graph as much as possible. It goes without saying that the very approach would be effective for other performance parameters including latency.

4 Onyx Mapping Algorithm

We aim at mapping each IP core of core graph on a tile so that a connection between tiles is established by the existing router in each tile. We have employed so-called Onyx, a heuristic method with little complexity and best results for mapping. As initially there is no mapping on NoC architecture tiles, and with cores mapping the possibility of better mapping would be decreased, cores with higher $comm_{i,j}$ should be mapped earlier. At first a core with the highest priority for mapping is determined by the function *highest-priority* ($G(V,E)$). Then the function finds the highest $comm_{i,j}$, and between the source core and its edge destination, the core with higher *ranking*(C_i) will be selected as the first choice. After selecting the first core

for mapping, a proper location on mesh based NoC architecture should be selected, as it can influence mapping procedure greatly.

$$Ranking(C_i) = \sum_{\substack{\forall j = 1, 2, \dots, |V| \\ i \neq j}} (comm_{i,j} + comm_{j,i}) \quad (7)$$

In mesh platform, with respect to the number of neighboring tiles, there are three types of tiles. Each tile, considering its location in the mesh platform may have 2, 3, or 4 neighbors. Hence, an appropriate router of each tile can be used resulting in 3x3, 4x4 or 5x5 (Fig. 2-a). Each tile may have different distances with every one of above-mentioned tiles. Considering mesh platform as a symmetrical platform, it is observed that in $n \times n$ mesh only

Fig. 2. (a) Candidate tiles for mapping the first core, (b) Concept of Lozenge-shape Path, (c) Definition of 4 Movements for moving on lozenge-shape path to determine priority of tiles for mapping, (d) A sample of selection of threes or fours order using 4 movements

$\sum_{i=1}^{\lceil \frac{n}{2} \rceil}$ i different tiles can be selected as the candidate for the location of first core. As other tiles have similar condition with one of this collection's tiles, the first core should be put on one of the candidate locations, and finally the most appropriate location will be determined. As represented by Fig. 2-a, *onyx* has selected the candidate tiles for mapping the first core.

As stated earlier, to get high performance, cores of the core graph which are tight related should be more adjacent on NoC architecture graph, and we attempt to reach such outcome in this research. To do so, while studying mesh platform as the communication infrastructure, it can be seen that as far as one tile in this NoC architecture concerned, tiles which have the same distance with the mentioned tile form a lozenge-shape path (Fig. 2-b). Following such method can decrease algorithm complexity and its execution speed, because if a core is going to be put in the nearest possible distance with its related core, first in the lozenge-shape path it looks for a unmapped tile with one hop and if it did not succeed it goes ahead to the two hops distance, and this mechanism continues until the empty tile is identified. *Onyx* goes along with 4 types of movement to determine the movement direction on lozenge-shape path (Fig. 2-c), and these types of movement also determine the tiles priority for mapping. In fact, relying on these 4 types of movement, it selects an order of three or four and follows the same order to the mapping end. To move on the lozenge-shape path it uses a movement on the line, and after core mapping it is the turn of next movement (Fig. 2-d). *Onyx* algorithm uses different, however limited orders of three or four with the help of 4 movements to achieve the best result. Therefore, after mapping the first core in one of the candidate locations, out of IP cores in core graph which are waiting for mapping, a core should be selected that has the highest *comm* with the mapped core, and then it should be placed in the shortest distance with it. Finding a location with such feature in terms of lozenge-shape path and priority and movement direction on it using an order of three or four would be easy. This procedure continues until mapping of all cores. More details are supplied in the following pseudo code (Fig. 3-a). The presented algorithm with focus on decreasing the number of hops between related cores can decrease *commcost*, and performance would rise consequently. The *commcost* is calculated as Formula 8:

$$commcost = \sum_{k=1}^{|E|} vl(d^k) \times dist(source(d^k), dest(d^k)) \quad (8)$$

5 Experiment Results

We have used VOPD and MPEG-4 real core graph to compare *Onyx* algorithm with other algorithms. For mapping VOPD, the order of $\alpha - \gamma - \alpha$ movements has been the best movement order on lozenge-shape path, and tile 5 is the best candidate for first mapping. For mapping MPEG-4, the order $\chi - \alpha - \gamma - \gamma$ and tile 6 have had the best condition. The movement orders are shown in Fig. 2-d. The ultimate results of mapping *Onyx* on core graphs VOPD and MPEG-4 are presented in Fig. 1. We have compared

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Initialize( G(V,E) , A(T,L) );
First_core = Highest_Priority( G(V,E);
For i=1 to  $\lfloor \frac{n}{2} \rfloor$ 
  For j=1 to i
    Candidate_tiles(k++)=(i-1)xn+j;
  For ( All candidates of first core location){
    First_tile = Candidate_tiles(cnt++);
    Map(First_core) = First_tile;
    Remove (First_tile from A, First_core from G and Add First_tile to
      Mapped_tiles ( T',L' ));
    best_cost = ∞;
    For (Different orders of three and four){
      Assign (G , A and Mapped_tiles to Temp_cores, Temp_tiles and
        Temp_mapped_tiles (T'',L''));
      If ( Order of three is used){
        Set (direction (1), direction (2), direction (3)); steps=3;
      }
      Else
        Set (direction (1), direction (2), direction (3), direction (4)); steps=4; }
      i=0;
      While (|V|>0){
        Hop=0;
        Assign (The vertex in Temp_cores with maximum "comm with
           $\forall t^{v_i} \in T'' + \text{vice versa}$ " to Next_core and  $t^{v_i}$  to Mapped_tile
        Main_direction = direction (mod (i, steps) +1);i++;
        While (It hasn't found unmapped tile) {
          Hop++;
          Search (For unmapped tile on lozenge-shape path with regard to
            Hop distance and Main_direction );}
        Assign founded tile to Next_tile
        Map (Next_core) = Next_tile;
        Remove (Next_tile from Temp_tiles, Next_core from Temp_Cores
          and Add Next_tile to Temp_mapped_tiles ( T'',L' ));
      For (Each  $d^k \in D$  ){
        Path = x-y routing algorithm (source( $d^k$ ),dest( $d^k$ ));
        Increase bw requirement for links in Path by  $vl(d^k)$ ;
        If (BW constraints are satisfied)
          Find the Commcost and store it in Cost
        Else
          Assign Max_value to Cost
        If ( cost <= Best_cost )
          Assign (Map, Temp_mapped_tiles, cost , First_tile and
            direction to Final_map, Final_tiles_Architecture,
            Best_cost, Best_first_tile and Best_directions;)}
      Return (Final_map, Final_tiles_Architecture,
        Best_cost,Best_first_tile,Best_directions );
  }

```

(a)

(b)

Fig. 3. (a) pseudo code of Onyx mapping algorithm, (b) Communication Cost of Different Mapping Algorithms on VOPD and MPEG-4 Core Graph

Onyx with NMAP, Partial Branch-and-Bound, GMAP, PMAP in [3] and BMAP [4]. In Fig. 3-b the minimum communication costs with the same bandwidth constraints for all algorithms are presented. As illustrated, our developed algorithm is showing best results.

6 Conclusion and Future Work

In this paper, a heuristic method for mapping the cores onto a tile-based NoC architecture was proposed in the way that tiles were connected to each other through a mesh interconnection. Onyx, defines four movements to assign priorities to the tiles on a lozenge-shape path, and appears to obtain better communication cost compared with a number of efficient mapping algorithms. Reducing the hop count between the directly connected cores in the core graph has a huge effect on the process of optimizing performance parameters such as energy consumption and latency. Onyx could obtain this goal, and seems to offer the most efficient method in reducing the hop count between the adjacent cores. The idea of implementing Onyx on other topologies can be an interesting subject for the further studies. Furthermore, since mapping is one of the most important sections in the process of designing NoCs, developing new optimization ideas to be used during the mapping procedure, could possibly lead us to much better results.