Traffic-Thermal Mutual-Coupling Co-Simulation Platform for Three-Dimensional Network-on-Chip

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ABSTRACTION

Thermal issue is one of the major challenges in the research field of three-dimensional (3D) IC. Network-on-Chip (NoC) has been viewed as a practical communication infrastructure for 3D IC. To facilitate such research, an accurate and non-proprietary environment for simulating the NoC traffic and temperature is necessary. In this paper, we present a traffic-thermal mutual-coupling co-simulation platform for 3D NoC. The translation error is eliminated, and therefore our co-simulation has no accuracy loss on mutual coupling. Our simulation results, validated with a commercial tool, show the temperature error of our platform is between -1 and 4 K. The simulation results also show the thermal profile of 3D NoC, in which the temperature is imbalance even under the balanced traffic. Hence, the proposed platform can be used for 3D thermal-aware design, 3D dynamic thermal management technology, and other related researches in the future.

1. INTRODUCTION

As System-on-Chip (SoC) complexity grows with Moore's law, on-chip interconnections gradually dominate the system performance. Network-on-Chip (NoC) has been proposed as an efficient and practical communication infrastructure [1]. As technology advances, three-dimensional (3D) IC technologies promise to reduce interconnect delays by connecting multiple dies through shorter vertical connections – Through Silicon Via (TSV) [2]. The combination of NoC and TSV, 3D NoC, is motivated to achieve lower connection cost, lower network power consumption, higher device density, and higher platform bandwidth [3].

Thermal issues are significant challenges to 3D IC and also 3D NoC because power density grows linearly when there are more dies stacked vertically. Due to the longer heat dissipation path, even with a balanced traffic distributed on the network, the temperature distribution is not balanced. With a given temperature limitation which can never be exceeded, such unbalanced temperature limits the network performance. Thermal-aware design and dynamic thermal management have been proposed to solve the thermal problems [4][5].

To facilitate the research for 3D NoC, a traffic-thermal mutual-coupling co-simulation platform is necessary. Traditional unidirectional coupling simulation platform cannot support developing these technologies, which is shown in Fig. 1(a). The simulator must not only simulate the traffic activities in 3D architecture, but also gets the temperature information during the network simulation. However,

FIGURE 1. (a) Unidirectional coupling simulation platform and (b) mutual coupling co-simulation platform

current non-proprietary NoC simulators do not support both features. Our co-simulation platform adopts the scheme proposed by Shang *et al.* [5], and the interaction of network traffic, power, temperature, and thermal management is shown in Fig. 1(b). During simulation, traffic activity on the given network model is observed from a NoC simulator. The network model gathers the traffic activities and inputs to the power model. The power model generates the spatial and temporal power consumption of the NoC system, which is a power trace. The thermal model calculates the temperature profile by the given power trace. The thermal management regulates the network traffic based on the observing temperatures of the NoC system.

Commercial Finite Element Analysis (FEA) tools, such as CFD-RC [6] and ANSYS [7], are not very suitable for the research of 3D NoC because the integration difficulty for mutual-coupling co-simulation, large overhead on hand-crafted model creation, and software cost are the major problems. FEA tools use the polygonal mesh model to build the precise shape of the object, and compute the more accurate temperature under Finite Element Method (FEM). The higher complexity also results in speed and translation problem. Available NoC simulators only provide a coarse granularity (module-level) model of the NoC system. To co-simulate with FEA tools, the power traces must be translated into polygonal mesh models, and the temperature model needs to be translated back to module-level models. Such translation might lose accuracy. To simplify the computation cost of thermal modeling, many works use Compact Thermal Model (CTM) instead of polygonal mesh and FEM. CTM is based on Fourier's law of heat conduction [8], and the thermal quantities in CTM are modeled as a network. Based on CTM, many simulation frameworks have been proposed. Shang *et al.* proposed a framework for online performance-temperature simulation, Sirius [5], which focused on the 2D NoC. Addo-Quaye proposed a 3D NoC simulation flow [9] by using the 3D extended version of HotSpot [8], which originally models the thermal profile of 2D IC.

This work is supported in part by the National Science Council, Taiwan, ROC, under Grant NSC98-2220-E-002-034.

This paper presents a non-proprietary 3D NoC traffic-thermal mutual-coupling co-simulation platform, which is available online¹. The correctness has been test with a typical 4x4x4 network combination, and the accuracy has been validated with commercial tool. Following the previous works, we integrate an open-source SystemC-based NoC simulator, Noxim [10], and the famous thermal modeling tool, HotSpot, at source level. HotSpot is extended to the 3D version, and Noxim is modified to support 3D NoC modeling, including supporting the 3D Dimensionally-Decomposed (DimDe) Router, proposed by Kim *et al.* [11], which allows a single-hop connection between any two layers, utilizing the short vertical connections of 3D IC. Our contributions are summarized as following for clarity:

- Develop a mutual-coupling traffic-thermal co-simulation platform and validate with a commercial tool.
- Extend the SystemC-based cycle-accurate NoC simulator to support common 3D architectures and routing functions.
- Eliminate the translation error by maintaining grid-level temperature trace and source-level integration.

The accuracy of the proposed 3D NoC simulator is validated by the FEA tool, CFD-RC. The validation result shows that the maximum temperature error of the proposed simulator is less than four kelvin (K). The result also shows the thermal profile of 3D NoC, in which the temperature is imbalance even under the balanced traffic.

2. RELATED WORKS

Sirius: Thermal Simulation of 2D NoC [5]

To address designs on the thermal management for 2D NoC, Shang *et al.* proposed an architecture-level simulation platform, Sirius. The thermal model in Sirius is constructed by the thermal RC network, based on the CTM. The commercial FEM tool, FEMLAB [12], is used to validate the thermal model in Sirius. And the validation results show the error against FEMLAB is less than 5%. A flit-level NoC model and an architecture-level network power model are built to evaluate the network performance and power consumption. Combining the network model, power model and thermal model, Sirius evaluates the network latency and throughput and on-line simulates the power consumption and temperature profile of 2D NoC. This paper also proposed a thermal management of 2D NoC based on Sirius.

Simulation Flow of Mapping for 3D NoC Designs [9]

Addo-Quaye proposed a simulation flow, which targets at the mapping for 3D NoC designs. A NoC simulator is constructed and evaluates the traffic activities. Based on the traffic activities, the power consumption is gathered from a synthesized hardware of 3D NoC system. The 3D-extended HotSpot calculates the temperatures of the 3D NoC system. The mapping is optimized based on the temperature information. The simulation flow provides accurate information for off-line mapping designs, but is not feasible for designs of the on-line thermal management.

FIGURE 2. Simulation for NoC traffic and temperature:
(a) unidirectional coupling and (b) mutual coupling

3. PROPOSED CO-SIMULATION PLATFORM

The proposed co-simulation platform for 3D NoC system couples the network model, power model and thermal model. We integrate Noxim [10] and HotSpot [8], and adopt the power model of Intel's 80-core processor [13]. Noxim is a cycle-accurate SystemC NoC simulator, and HotSpot provides the architecture-level thermal model. To coupling with HotSpot, the NoC simulator should convert its architecture-level floorplan and power trace to chip-level physical floorplan and power trace. We first add the model of basic 3D router and the DimDe router, and we extend Noxim to be able to generate 3D architectures of NoC based on user-defined parameters. Then a module is inserted for automatically converting the architecture-level floorplan to physical floorplan. During network traffic simulation, a power trace is generated based on the power model of the NoC. The power trace and physical floorplan are used as inputs of the thermal simulation. In the proposed simulator, the tile geometry and power model are based on Intel's 80-core chip.

Unidirectional Coupling and Mutual Coupling

The straightforward simulation approach is the unidirectional-coupling simulation: HotSpot runs after Noxim finishes, as shown in Fig. 2(a). Unidirectional-coupling simulation gathers the entire temporal and spatial power trace of the chip from Noxim, and then computes the transient temperatures and the steady temperatures in HotSpot. The problem of unidirectional-coupling simulation is that the network simulator cannot get any temperature information before thermal simulation. The overall temperature trace from t_{start} to t_{finish} is computed after the network simulator generates the overall traffic and power traces from t_{start} to t_{finish} . Therefore, unidirectional-coupling simulation cannot be used for verifying thermal-aware designs or dynamic thermal management techniques for 3D NoC.

The mutual-coupling co-simulation scheme has to be incorporated for verifying thermal-aware design or dynamic thermal management techniques. The change of workload on NoC instantly effects the following small period power distribution and traces of the network, and consequently the following small period of temperature distribu-

¹ <http://access.ee.ntu.edu.tw>

tion and traces. The network simulator computes a period of traffic and converts it to a power trace. The period is usually set from 10^{-4} to 10^{-2} second. The transition temperatures are computed right after simulations of the short period network traffic. Fig. 2(b) shows the mutual-coupling co-simulation scheme. We begin the integration at source level, and use Noxim as caller to call the program interface of HotSpot to feed, compute, and feed back the temperature for each small period of time. HotSpot takes the architecture-level temperature distribution as the input for initial condition, and uses the small period of the architecture-level power trace P and the chip floorplan as inputs to generate the short-term architecture-level thermal profile T . The overall simulation forms a looped mutual coupling between Noxim and HotSpot.

Translation-Error-Free Mutual Coupling

On computing transient temperatures, we observed that the program interface of HotSpot causes the translation error. Since the input and output of HotSpot are coupled to Noxim, they have to be translated. Fig. 3 shows the comparison between the original and translation-error-free mutual coupling co-simulation. Hotspot computes the temperature transition from t_{i-1} to t_i , and the distribution at t_i is forward translated and fed to Noxim for simulating a thermal-aware design. The forward translation from grid level to architecture level is done by averaging the power and temperature numbers of grids. Noxim then simulates the traffic from t_i to t_{i+1} . If the NoC is thermal-aware, it may adjust traffic based on the temperature distribution for not exceeding thermal limit or for better heat dissipation. The architecture-level power trace for thermal simulation is then generated during network simulation. The backward translation from Noxim to HotSpot, from architecture level to grid level, is done by assigning all grids with architectural power and temperature.

Elimination of Translation Error

Forward translation loses accuracy of temperature. In network simulator, the averaged temperature has fine enough granularity for thermal-aware technology. However, for thermal simulation, such loss causes inaccurate temperature transition. The initial state for the period from t_i to t_{i+1} is inaccurate, which causes error accumulation. Besides, the discontinuous boundary condition makes involuntarily heat conduction on the grids on the architecture-level boundary. To eliminate the forward and backward translation error, we remove the program interface of HotSpot and integrate both tools at source level. Fig. 3 shows our translation-error-free mutual-coupling simulation scheme. The grid-level data structure is maintained during the whole simulation, and therefore the forward translation does not make data loss before backward translation. On each small period of time, the network simulation part, modified Noxim, generates the power traces based on the power model and feeds them into the grid cells. The thermal simulation part, modified HotSpot, computes a small period of time of the temperature transition from a temperature distribution that has accurate initial state and boundary condition. The temperature profile is then fed back to Noxim right after the simulation, which can be used as the sensed information for thermal-aware NoC design, such as dynamic thermal management.

FIGURE 3. Original and translation-error-free mutual-coupling co-simulation

4. VALIDATION AND RESULT ANALYSIS

Validation with CFD-RC

To ensure the accuracy of the proposed co-simulation platform, we validate our approach with the commercial thermal modeling tool, CFD-RC. Original HotSpot is evaluated by viewing the ANSYS results as the ground truth, and we follow this validation approach. The validation of the original HotSpot is done by using a conventional 2D IC for simulation setup. The evaluation in [8] shows the allowable temperature error ranges between -1 and 4 K. For the 3D structure, we specify the validation of the vertical heat dissipation. The heat sink and heat spreader are modeled as a piece of copper, whose size is 8 mm × 6 mm × 7.9 mm. The dimensions of silicon dies are 8 mm × 6 mm × 0.15 mm, which contains a 4 × 4 mesh NoC. The power density of the tile model in [13] is 667 kW/m², which is the power density of a 2D chip. Such high power density leads to the unreasonable high temperature for the real 3D stacked system. Therefore, we scale the power density to 0.5. Between any two dies, the thermal interface material layers are inserted and with a thermal conductivity of 4 W/(m · K). The ambient temperature is 300 K. By setting the same simulation environment, the validation result in Table 1 shows the temperature error to CFD-RC ranges between -1.06 and 3.94 K, which is similar to [8]. The validation result shows that the vertical temperature distribution is modeled accurately in 3D-extended HotSpot in our simulator.

TABLE 1. Temperature Comparison to CFD-RC (Unit:K)

	CFD-RC (K)	This Work (K)	Error (K)
Layer 0	340.98	344.92	+3.94
Layer 1	339.65	342.78	+3.13
Layer 2	337.09	338.48	+1.39
Layer 3	333.10	332.04	-1.06

FIGURE 4. A 4-layer 3D NoC with heat sink for validation

FIGURE 5. Temperature distribution for typical traffic patterns of 3D NoC: (a) uniform traffic (b) transpose traffic (c) hotspot traffic.

Simulation for Typical 3D NoC Traffic Patterns

To demonstrate the unbalanced temperature distribution of 3D NoC, we utilize the proposed traffic-thermal mutual-coupling co-simulator to simulate typical traffic patterns of 3D NoC. The simulation result indicates further thermal-aware algorithms and thermal management scheme for 3D NoC is required. All the experiment is on a $4 \times 4 \times 4$ mesh NoC system, with buffer depth = 4 flits and packet length = 6 flits. The packet injection rate is set to 0.005. The tile model is from 80-core NoC system. The router is DimDe router. The ambient temperature is set to 45 °C.

In Fig. 5(a), the thermal map shows the imbalance of a 3D system even given a uniform traffic pattern. The stacking dies of the 3D structure introduce the different thermal characteristics on each layer. The lowest temperature tends to locate at the bottom layer which is close to the heat sink, while the top layer is at the highest temperature. And the floorplan of the tile model results in the different thermal characteristics within a layer. The highest temperature over the tile is located on the router due to the high power density. When 16 tiles form a mesh layer, the routers along the left and down side of the layer have less low-temperature space for the heat dissipation. Within a layer, the temperatures distribute diagonally from high to low. However the down and leftmost tile is at a lower temperature to the neighboring tile, because the corner traffic is less congested under the uniform traffic.

In Fig. 5(b), the thermal map shows the thermal hotspots are shifted to the bisection of the network under the transpose traffic patterns. The transpose traffic results in a more congestion on the bisection of the network. And we also see the similar temperature imbalance in the horizontal and vertical direction.

Under the hotspot traffic patterns, we set a traffic hotspot at the bottom layer and with a probability = 0.1. The traffic hotspot is placed at the bottom layer, and the corresponding thermal map is in Fig. 5(c). The traffic hotspot at the bottom layer leads to the thermal hotspot. The thermal hotspot at the bottom layer blocks the vertical dissipation path. The temperatures of tiles above the traffic hotspot go up due to the blocking, and the thermal hotspot becomes the “hot column.” And the other tiles have the similar temperature distribution to the uniform traffic.

TABLE 2. Qualitative Comparison with Related Works

	Ref. [5]	Ref. [9]	This Work
Supporting 3D NoC		○	○
Mutual-Coupling Co-Simulation	○		○
Validation	○		○

Qualitative Comparison

A qualitative comparison between this work and related works are summarized in Table 2. Our work joints the advantages of the two related works so our work can achieve mutual-coupling co-simulation on 3D NoC. Moreover, compared with [5], our simulation results show the absolute temperature error, and the relative error is much smaller.

5. CONCLUSION AND FUTURE WORK

In this paper, we present the idea and approach of our traffic-thermal mutual-coupling co-simulation platform for 3D NoC. The validation shows our simulation results achieve the equal accuracy to HotSpot. The simulation results also show the thermal profile of 3D NoC, in which the temperature is imbalance even under the balanced traffic. This phenomenon is different from the 2D cases. Hence, the proposed platform can be used for 3D thermal-aware design, 3D dynamic thermal management technology, and other related researches in the future.

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