**A Nearest-Neighbor-Based Thermal Sensor Allocation and Temperature Reconstruction Method for 3-D NoC-Based Multicore Systems**

Based on the analysis of the previous approaches, we find that the current thermal-sensing NoC-based multicore system design has two design challenges:

1. The flexible allocation of number-limited sensors that can adapt to different applications
2. The accuracy of full-chip temperature reconstruction that requires acceptable computing latency and hardware cost.

In this article, we allocate the number-limited thermal sensors based on the spatial thermal correlation of the cores, and the relative position of the cores will not change as the chip works under different applications. Besides, we use an artificial neural network (ANN) to estimate the temperature of nonsensor-allocated nodes.

The contributions of this article are summarized as follows:

1. We propose the nearest-neighbor-based thermal sensor allocation method. Previous work [20] has proven that the temperature correlation of different cores in the multicore system is mainly related to their distance. Based on the spatial correlation, we propose the nearest-neighbor-based initialization algorithm to make thermal sensors surround every nonsensor-allocated core. We then use the genetic algorithm (GA) to optimize the initial sensor allocation to adjust the number of obtained sensors.
2. We propose the ANN-based full-chip temperature reconstruction method. We can get the accurate temperature of these sensor-allocated nodes from the allocated thermal sensors. Due to the temperature correlation, these nodes also contain temperature information of other nonsensor-allocated nodes around them. We can express the hidden temperature information explicitly with ANN to estimate the full-chip temperature precisely.

**NEAREST-NEIGHBOR-BASED THERMAL SENSOR**

* The proposed method allocates thermal sensors based on spatial correlations, which remain consistent regardless of application workloads, enhancing flexibility in temperature reconstruction.
* We can conclude that the correlation of two nodes is mainly dependent on the distance between them, and the farther their distance is, the less correlation they have. In other words, the correlation defined by (1) will not change when the chip works under different workloads.
* A mathematical model is introduced to optimize sensor placement, ensuring that each nonsensor-allocated node has nearby sensors to improve temperature estimation accuracy.
* We propose a nearest-neighbor-based thermal sensor allocation method. Our method aims to allocate thermal sensors around the nodes without sensors. Because of their close distance,their temperature information has a high correlation. Therefore, nonsensor-allocated nodes’ temperature can be estimated by the sensor-allocated nodes around them.
* Although the sensor allocation obtained by the initialization algorithm (NEAREST-NEIGHBOR) can meet the constraints, the number of sensors cannot be adjusted according to the constraints of the hardware cost. Therefore, we use GA to explore the optimal sensor-allocated locations for different sensor numbers.

Allocation Optimization Using GA

* The GA framework defines chromosomes and fitness values to evaluate sensor placements, allowing for adjustments based on hardware constraints.
* The method can adapt to varying numbers of usable sensors while maintaining effective temperature reconstruction.

**ARTIFICIAL-NEURAL-NETWORK-BASED FULL-CHIP TEMPERATURE RECONSTRUCTION TECHNIQUE**

* Use **ANN** to estimate the temperature of the nonsensor-allocated nodes.
* A lookup table is utilized to determine which sensor measurements serve as inputs for the ANN, facilitating efficient temperature reconstruction.

**Structure of the ANN**

* The structure of the ANN we use is shown in Fig. 3. It has one input layer, two hidden layers, and one output layer, and they are fully connected layers. Additionally, we select the rectified linear unit (ReLU) function as the activation function.
* The cost function is designed to minimize the difference between estimated and actual temperatures, ensuring precise outputs.
* cost = *(*Output − Actual*)*2
* **Output** is the output of the **ANN**, and it is the estimated temperature. **Actual** is the actual temperature of the node.

**Lookup Table Building**

* A systematic approach is used to populate the lookup table, ensuring that the ANN receives valid input data for temperature estimation.

**EXPERIMENTAL RESULTS AND ANALYSIS**

* To obtain the temperature data for the **ANN** training and model evaluation, we implemented an 8 × 8 × 4 mesh-based 3-D NoC-based multicore system on a cycle-accurate traffic-thermal NoC simulation tool—**AccessNoxim** [22]. Each node in the NoC-based multicore system consists of a multiply-accumulate (**MAC**) block.
* The temperature data under these three traffic distributions are collected as the training data for sensor allocation and **ANN** training.

**Six Sensors Around or Three Sensors Around**

* In Section III-A, we propose using three sensors instead of six sensors to decrease the number of sensors and the cost. As shown in Fig. 7, using six sensors has a slight improvement in accuracy, about a 6.33% decrease in the average temperature error. This minor improvement is negligible compared to the huge expenses.

**Robustness**

* The method exhibits high robustness, as indicated by a low coefficient of variation across multiple trials, confirming the reliability of the sensor allocation.

**Optimizing Search**

* The GA's performance is enhanced by the proposed initialization algorithm, leading to better solutions within the same time frame compared to random methods.

**Average and Maximum Temperature Error**

* The proposed method consistently outperforms state-of-the-art techniques in reducing both average and maximum temperature errors across various scenarios.
* The average temperature error of our approach is equivalent to [12] and better than [15] when it comes to known traffic patterns. For real applications, our approach reduces the average error by 17.60%–88.63% compared with state-of-the-art methods.
* The maximum temperature error of our approach is equivalent to [12] and better than [15] under known traffic patterns. For real applications, our approach reduces the maximum temperature error by 26.97%–85.92% compared with state-of-the-art methods.
* For unknown real applications, our proposed method has the minimum error among these methods. This is because methods [12], [15], [19] depend on the training data. When the work scenarios differ from the offline training dataset, the cores’ thermal relationship used in these methods will change. However, our sensor allocation algorithm is based on spatial correlation, and this relationship does not vary as the application scenario changes.

**Stability**

* The method maintains low average temperature errors even with varying sensor counts, demonstrating its adaptability to different application scenarios.
* For unknown real applications, which are the more realistic scenarios, our method consistently has the lowest average temperature error with different numbers of sensors.

**Hardware Cost:**

* The proposed approach balances hardware costs effectively, requiring fewer resources than more complex models while maintaining performance.

**CONCLUSION**

* The thermal problem is serious in NoC-based multicore systems, especially when 3-D NoC-based multicore systems emerge. To prevent overheating, thermal sensors are usually embedded in the system to monitor the temperature for control, but their number is often limited due to cost. In this article, we propose a thermal sensor allocation method based on spatial correlation and **GA**. Additionally, to reconstruct the full-chip temperature, we use **ANN** instead of linear methods to learn the correlation information between nonsensor-allocated nodes and sensor-allocated nodes.
* Compared with the conventional approach, our approach reduces 17.60%–88.63% average temperature error for the unknown real applications

Limitations:

* The proposed method relies heavily on the spatial thermal correlation of cores. If the actual thermal behavior deviates from the expected correlation due to unforeseen application characteristics, the accuracy of temperature reconstruction may be compromised.
* Hardware Overhead: