Network on Chip Design and Optimization Using Specialized Influence Models[*]

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ABSTRACT

In this study, we propose the use of specialized influence models to capture the dynamic behavior of a Network-on-Chip (NoC). Our goal is to construct a versatile modeling framework that will help in the development and analysis of distributed and adaptive features for NoCs. As an application testbench, we use this framework to construct a design methodology for dynamic voltage and frequency scaling (DVFS). We also point out similarities of the proposed model with backpressure mechanisms that could be potentially exploited toward enhanced models for estimation and optimization of NoCs.

Categories and Subject Descriptors

B.7.1 [**Integrated circuits**]: Types and design styles—*advanced technologies*

General Terms

Algorithms, Design, Performance, Optimization

Keywords

Network on Chip, Influence model, VFI design style

1. THE INFLUENCE MODEL

The influence model strips away the specific details of component models and offers a simple and analytically tractable model of the dynamics of systems comprised of n interacting Markov chains [1]. Chains are associated with vertex *sites* (or nodes) and they may differ in their order and structure. Each site i assumes one of a finite number m_i of possible statuses at each discrete time instant. The model evolves by updating the statuses of all sites in discrete time. Each site i changes its status from $s_i[k]$ at time k to $s_i[k+1]$ at time $k+1$ in accordance to a probability vector $p_i^T[k+1] = s_j^T[k]A_{ji}$, where $s_j[k]$ is the status of the *determining* neighboring site j and A_{ij} is a fixed row-stochastic $m_j \times m_i$ matrix. The determining site j is selected with probability d_{ij}. Probabilities d_{ij} define the *network graph* associated with the influence model and they are assembled to form the network influence matrix $D = [d_{ij}]$. The evolution of the influence model can be written collectively for all n sites in compact form as [1]:

$$\mathbf{p}^T[k+1] = \mathbf{p}^T[k]H \tag{1}$$

where $\mathbf{p}[k]$ is the matrix formed by stacking $s_i[k]$ of all n sites, and H is a matrix whose entry (i, j) is given by the product $d_{ji}A_{ij}$, and is generally not a stochastic matrix. The influence model with A_{ij} being the same for all n sites is referred to as the homogeneous influence model. An example of a network graph associated with a 3×3 mesh NoC topology is shown in Fig.1. The interaction between sites is captured by the matrix D, while the determining site j impacts how the current site i changes its status via matrix A_{ij}. The evolution of the model leads to a natural partitioning (or islanding) of all the nodes. This will be discussed in the next section.

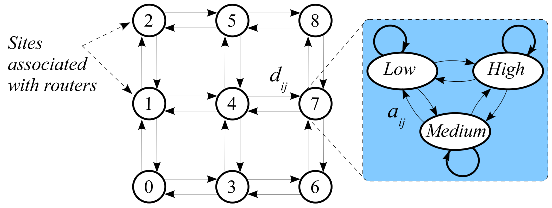

Figure 1: The network graph associated with a 3×3 mesh NoC, as a graphical depiction of the influence model. The right hand-side shows the expanded view of one site, with statuses *Low*, *Medium*, and *High* usage of the buffers of the associated router.

We propose to employ the influence model in order to build a NoC modeling framework that is simple enough, and yet that offers meaningful ways to track the spatially and temporarily correlated behaviors of the network. Using this as a basis, we discuss dynamic voltage and frequency scaling (DVFS) as a pilot application for the proposed model.

2. DYNAMIC VOLTAGE AND FREQUENCY SCALING

Globally asynchronous locally synchronous (GALS) represents a promising design paradigm to address the global-interconnect delay problem. It also fits well with the voltage-frequency islands (VFI) design technique introduced for achieving fine-grain system-level power management. In the context of NoCs [2], a recent study showed that VFI can offer significant energy savings [3]: this is achieved by doing *centralized static* VFI partitioning and voltage/frequency assignment, and then *online* dynamic voltage and frequency scaling *around* the solution found in the first step. We propose to take this idea one step further and design a *decentralized (i.e., distributed) dynamic* VFI partitioning methodology. This will enhance the adaptive and self-healing capabilities of NoC based systems to address changing environmental conditions or to implement fault-tolerant mechanisms. **Our idea is to implement a distributed algorithm, based on the homogeneous influence model from the previous section, which shall dynamically**

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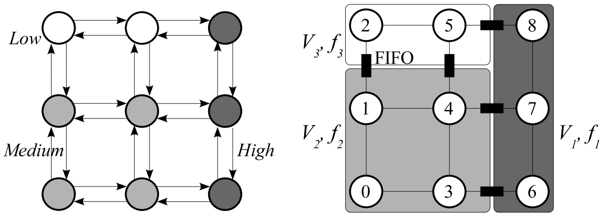
perform VFI *islanding* in response to changes in application traffic or of the application itself.

To build the specialized influence model, one can place traffic monitors on each of the physical channels of the NoC and use their reading to compute probabilities d_{ij}. Intuitively, the probability d_{ij} should be a proportional measure of the amount of traffic between two adjacent routers. Inside our model, that will mean that from among all neighbors of a router i, the one that sends the largest amount of traffic, say router j, should have a higher *determining* impact on the status of router i. In other words, if a router is surrounded by routers with increased traffic (i.e., higher buffer utilization, status *High* in Fig.1), its status will likely be influenced toward having a lot of traffic too. Whenever a new application is implemented by the NoC based system, the main steps to do distributed VFI partitioning are:

1. The specialized influence model is initially reset, and then evolved for a specified time interval - given by an adaptive stopping strategy.
2. The model evolution leads to a network *islanding* that represents the basis for VFI partitioning (see Fig.2.a).
3. Voltages and frequencies are assigned to islands so that the application is geared toward an energy-saving mode while satisfying performance constraints[1] (see Fig.2.b).



(a) (b)

Figure 2: (a) Statuses of the influence model after the evolution time interval. (b) NoC VFI partitioning with voltage/frequency assignments.

3. FURTHER CONSIDERATIONS

The advantage of the influence model over a master discrete time Markov chain is that the influence matrix H has a far smaller dimension $\sum_i m_i$ compared with the size $\prod_i m_i$ of the associated state-transition matrix G of the master chain. However, G and H are intimately related, and it is this relationship that can be exploited in order to convert computations involving G to reduced-order computations involving only H. This allows one to make inferences about the limiting behavior of the master chain through the study of the much smaller influence graph.

Even though we used DVFS as a pilot application to present our ideas, the proposed model may be used to design other system level optimization algorithms. For example, the islanding achieved by the model may be used to design task migration techniques in order to implement thermal management policies or to facilitate fault tolerant mechanisms. Such policies and mechanisms will improve the long-term reliability of the NoC. Due to its distributed nature, the influence model can accommodate router failures. If for example, a router suffers a permanent failure, then, the influence model can update itself by removing the corresponding arcs from the influence network (Fig.1) and by updating the local d_{ij} probabilities.

The status of a site i at time step $k+1$ is determined by the status of neighboring site j from time step k, which at its turn had been determined by the state of a neighboring site, say u, from time step $k-1$, and so on. We note an analogy between this recursive relationship and the back-pressure mechanism in NoCs. This suggests that the proposed model could incorporate predictive explicit-rate control mechanisms in order to adjust source traffic rates [4] for congestion optimization and to facilitate guaranteed quality of service [5].

The status occupancy probabilities for each site at any time is determined based only on the individual status occupancy probabilities of itself and of all the neighbors at the previous time step (or from knowledge of the initial state of the network) [1]. Information about occupancy probabilities may be employed in designing for example application-specific *static* buffer allocation (a primary concern during NoC synthesis) algorithms. Also, by dynamically tuning the probabilities d_{ij}, the model could account for the impact of congestion, as opposed to static models that assume known packet delay when traversing network routers (which becomes inaccurate and can break performance constraints guarantees).

Finally, we would like to point out that the influence model has further ramifications in other application domains, including multicasting in ad-hoc networks, self-classification for autonomous vehicles, and distributed decision-making [6].

4. CONCLUSIONS

We proposed a novel modeling framework for NoC design based on the influence model. This framework was used to develop a design methodology for GALS and VFI based design style for NoCs. We hope that the influence model, as a generalization of prior stochastic models, will facilitate the development of distributed and adaptive features for NoCs. This fits the vision of network-based computational models outlined by [7].

5. REFERENCES

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[1] We assume a rich availability of mixed clock/mixed voltage FIFO queues (used for communication across different islands), though in practice one would limit their number in the interest of silicon area.