Communication Models in Networks-on-Chip

Everton Carara, Aline Mello, Fernando Moraes
Faculdade de Informática – PUCRS – Av. Ipiranga 6681, Porto Alegre, Brazil
{carara, alinev, moraes}@inf.pucrs.br

Abstract

Networks-on-chip, or NoCs, are one communication architecture candidate to be used in present and futures SoCs, due to its scalability, reusability and performance. The focus of this paper is the analysis of IP communication models in NoCs. Employing standard external interfaces, as OCP, is recommended to enable the use of NoCs by different IP core providers. The second point related to reusability is the IP cores communication model. Two basic communication models are considered in this work: NUMA and NORMA. The goal of this work is to evaluate the pros and cons of each communication model, in terms of network interface complexity, area and performance.

1. Introduction

NoCs [1] are emerging as a possible solution to the existing interconnection architectures due to the following features: (i) energy efficiency and reliability; (ii) bandwidth scalability when compared to the traditional bus architectures; (iii) reusability; (iv) distributed routing decisions.

The IP cores as well as the interconnection structures should fulfill the design reusability requirement, using a standard protocol (e.g. OCP) between then. Using a standard interface does not change the way IP cores are developed, since they will still be developed for a certain protocol. What changes is that a public domain protocol is used and accepted by the industry as a standard, as occurred with the PCI standard for microcomputer manufacturers. Thereby, IP cores reusability becomes higher and design time is reduced since cores integration turns into a simpler task.

Using a standard protocol the NoC can be seen as a communication IP. This simplifies the communication, making the NoC as transparent as possible to the IP cores using it. Besides the standard interface, a communication model must be adopted. Examples of communication models are NUMA (non-uniform memory access) and NORMA (no remote memory access).

The goal of this work is to investigate the performance of NUMA and NORMA communication models in NoCs, evaluating which of the models better explores the NoCs resources and performance. During the development of this work, HERMES [2] is used as an NoC case study.

2. Related Work

Researchers have proposed NI (network interface) designs to provide communication services to the IP cores connected to the NoC considering: (i) low area cost, (ii) high throughput, (iii) low latency, (iv) reusability. This Section presents NI designs employing the NUMA communication models. UMA model is not appropriate for SoCs, due to the usual distributed memory architecture.

Liu et al. [3] propose a NI supporting multicast traffic and it is implemented with random access memory at the input and output channel. An important feature of the NI is that different numbers of input and output signals are supported. In this way, the NI controls the multiplexing/demultiplexing unit to map the signals of the IP cores to/from the router.

Bertozzi et al. [4], developed a NI based on OCP protocol to interconnecting IP cores (master, slave or both) to the Xpipes. The NI has a parameterizable buffer at output port that increases the NI area. On the other hand, that leads to reduce the communication latency. This work also presents an infrastructure with allows the high-level abstraction of the NoC, modular design, and differentiated services.

Radulescu [5], presents a NI to the Æthereal NoC that adopts DTL and AXI protocols. The NI also provides time guarantees (e.g., bandwidth and latency bounds), and offers a solution to NoC and IP modules configuration at runtime. This NI decouples computation from communication using a shared-memory abstraction, which is independent of the NoC implementation. The NI is composed by two parts: (i) NI kernel – which implements the channels, packets segmentation and end-to-end flow control; (ii) NI shells – which is responsibly by the transaction ordering and connections (e.g, multicast).

The common features of the herein proposed work with the works described above are: (i) adoption of standard protocol; (ii) low area cost; (iii) infrastructure for NoCs and NIs specification and generation [6]. In addition to the others previously reviewed works, to the best of our knowledge, our NI is the first one to address the NORMA model implementation.

18th IEEE/IFIP International Workshop on Rapid System Prototyping(RSP'07)
0-7695-2834-1/07 $20.00 © 2007 IEEE

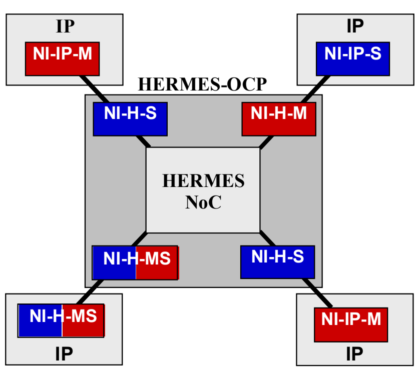
3. Network interfaces

Unless the IP core uses the same communication protocol as the network, it is necessary to create a wrapper to connect the IP core to the network, called here network interface (NI). NIs usually provide services at the transport layer of the OSI model, because this is the first layer where the services are independent from the network structure. This is a key factor to achieve the decoupling between computation and communication, which enables IP cores and the interconnection structure to be designed independently [5].

According to Kumar [8], it is possible to divide the NI internal design in two parts: (i) network specific part, independent from the IP core, responsible for temporization, buffering and synchronization aspects during data send/receive; (ii) core specific part, responsible for packets segmentation/ reassembly.

With the goal to increase the HERMES reusability, the OCP protocol is employed between the NoC (Local port) and the IP cores. OCP defines a point-to-point interface between two IP cores. One of these operates as master and the other as slave [7]. The HERMES network with OCP interface is named HERMES-OCP (Figure 1).

It must be emphasized that in order to be able to communicate using HERMES-OCP, an IP core must follow the OCP protocol adopted by the network. It is not sufficient to have compatibility between used signals and their widths. A communication protocol must be defined by the network and adopted throughout the system. In other words, HERMES-OCP physical layer adopts the OCP protocol, the link layer defines a packet format, composed by a sequence of OCP transactions and the network layer is a point-to-point communication that can be different for each pair of cores.



NI-H means Hermes Network Interface. It can be of types *slave, master,* or *master-slave (all developed for HERMES).* **NI-IP** is the Network Interface at the IP side, and it can also be *slave, master,* or *both.*

Figure 1 - Types of NIs that can be connected to the HERMES-OCP.

3.1 NORMA network interface

The NORMA communication model does not assume the existence of a global address map. Communication is achieved directly, through the exchange of messages between IP cores. In a NORMA system, cores are independent, providing services they can offer to the other IP cores. However, the IP cores have to deal with the overhead of changing their communication paradigm and be concerned about packet segmentation/reassembly, due to the arbitrary size of messages. This work employs an interface formed by the OCP basic signals together with the *SRespAccept* signal.

For *read* and *write operations*, a set of OCP transactions is transmitted through the NI-IP-M to the corresponding NI-H-S (Figure 1).

In a write *operation*, OCP transactions are transmitted through the NI-IP-M to the NI-H-S. The first transmitted flit corresponds to the destination IP address, followed by the flit containing the size of the payload and then the payload itself.

In a *read operation*, the NI-IP-M sends the packet header to the NI-H-S through two write commands. The payload corresponds to the addresses where data should be read, being sent using read OCP commands (*MCmd=rd*). Each OCP read operation generates an answer of the NI-H-S to the NI-IP-M. When the signal *SResp* contains DVA, valid data is present in the *SData* signal. The read commands are non-blocking and there is no path allocation on the network for returning the answer. In this way, multiple requisitions can be made sequentially, independently from receiving the answers.

3.2 NUMA network interface

The NUMA communication model has a single address space and is very similar to that used in bus architectures. The designer's role when using this model is to define the memory map and to avoid conflicts between the IP cores. This reduces core reusability. In a NUMA system, messages are typically short and composed by address and data.

This model uses the same interface signals as the NORMA model. However, the MAddr signal has a width between 8 and 32 bits and it is used to send two types of information: (i) destination IP core address and (ii) IP core internal address, used for read or write operations.

The NUMA model simplifies communication, because the write and read operations are performed in the same OCP transaction. Each OCP transaction also corresponds to a single packet travelling in the network.

In write operations, a NI-IP-M transmits to a NI-H-S a transaction containing the write command (MCmd=wr), the address partitioned in destination IP address on the network and IP internal address (MAddr), and data (MData).

In a read operation, the NI-IP-M transmits to the NI-H-S a transaction containing the read command (MCmd=rd), and the partitioned address.

The answer corresponding to the read operation is transmitted from the NI-H-S to the NI-IP-M when the content of the SResp signal is DVA. As in the NORMA model, there is no path allocation on the network for the return of the answer and multiple requisitions may happen independently from receiving the answers.

4. Wrapper development

The SR8-OCP system was developed as a case study aiming to validate the interconnection and communication of the cores with the OCP standard interface (master, slave and master-slave) through a 2*x*2 network. Four IP cores compose this system: two memories (Block SelectRAM) connected to an NI-IP-S; a serial interface module (to communicate with a host computer) connected to an NI-IP-M; and a processor connected to an NI-IP-MS.

Once defined the HERMES-OCP parameters: (*i*) flit width of 16 bits; (*ii*) queues depth of 8 flits; (*iii*) XY routing algorithm; (*iv*) 2x2 mesh topology; (*v*) two NI-H-M, one NI-H-S and one NI-H-MS, it is necessary to establish how the packets will be interpreted between source and destination IPs. The first flit of the payload is thus named *command flit*, and is responsible to identify the packet function.

Only the processor wrapper (R8-OCP) for the two communication models is presented. Four IPs compose the R8-OCP: (*i*) local memory; (*ii*) R8 processor (small 16-bit RISC processor); (*iii*) OCP Master interface (NI-IP-M); (*iv*) OCP Slave interface (NI-IP-S). The NI-IP-M is connected to the R8 processor while the NI-IP-S is connected to the local memory.

4.1 NORMA wrapper

In this communication model, the designer must be familiar with the structure of the packets sent through the network. In the SR8-OCP case study, five packet formats identified by the command flit (e.g. command 1) are used, as depicted in Figure 2.

Simple Write

MCmd	WR	WR	WR	WR	WR
MData	Target	Payload size	Command 1	Address	Data

Simple Read

MCmd	WR	WR	WR	RD
MData	Target	Payload size	Command 2	Address

Burst Write Mode 1

MCmd	WR	WR	WR	WR	WR	WR	...	WR	WR
MData	Target	Payload size	Command 3	Number of Words	$Address_1$	$Data_1$	...	$Address_N$	$Data_N$

Burst Write Mode 2

MCmd	WR	WR	WR	WR	WR	WR	...	WR
MData	Target	Payload size	Command 4	Number of Words	Initial Address	$Data_1$	...	$Data_N$

Read Response

MCmd	WR	WR	WR	WR
MData	Target	Payload size	Command 9	Data

MCmd and Mdata are OCP signals.

Figure 2 - Format of the packets in the SR8-OCP case study.

When the R8 processor executes write or read operations, it is necessary to identify if its destination is the local memory or another IP of the system. For this reason, remote write and read operations are memory mapped to the 0xFFFF and 0xFFFE addresses, respectively.

The NI-IP-M starts read and write operations while the NI-IP-S can send a read response. The NI of HERMES are responsible to avoid conflicts when both NI-IP-M and NI-IP-S try to communicate with the NoC simultaneously. At the NoC side, the incoming packets should be directed to the NI-H-S or to the NI-H-M. When the command flit is equal to 9 (read response) the packet goes to the NI-H-S and then to the NI-IP-M, otherwise the packet goes to the NI-H-M and then to the NI-IP-S. All possible conflicts are solved at the NoC side, simplifying the design of the NI-IP-M and the NI-IP-S.

4.2 NUMA wrapper

When using the NUMA communication model, a global address map must be previously defined and accepted by all IPs (e.g. Figure 3).

Address	Target IP
0x0000 - 0x03FF	00
0x0400 - 0x07FF	10
0x0800 - 0x0BFF	01
0x0C00 - 0x0FFF	11

Figure 3 - Example of global address map.

In the NUMA model the user does not need to be familiar with the structure of the packets being transmitted through the network, which is transparent to him/her. On the other hand, the user needs to know the global address map. The NI-IP-M has to check the address map to determine the destination IP for the write or read operations and to create the OCP transaction.

It is important to stress that the NUMA communication model does not easily support burst transmission, since the model assumes read and write operations directly mapped in a single shared memory map. Therefore, to send five words for the IP with address 10, five packets are transmitted, while in the NORMA model only one packet is transmitted.

This example illustrates the two main differences between the models. The first one is *complexity of the wrappers on the IP core side*. In the NORMA model, besides generating the OCP transactions it is necessary to explicitly create the packets that will be transmitted through the network. This may be done either in software or with dedicated hardware. In the NUMA model, the function of the wrapper is simply to generate OCP transactions. The second one is the *flexibility* of the modes for exchanging messages between the IP cores. At the NORMA model, it is possible to send any content whose semantics is defined by the service specified in the payload. In the NUMA model there are only single read and write operations.

5. Results

For the area comparison, the case study presented in the previous Section is employed. The area consumption for the HERMES-OCP, independently of the communication model, is practically the same for a FPGA mapping. For ASIC mapping a difference is observed in favor of NUMA, due to the NIs area. The complexity of the NORMA NIs is superior to the complexity of the NUMA NIs, since they should interpret the packet function. At the IP side, the same result is observed: NUMA presents an advantage over NORMA due to the NIs complexity. However, this case study employs low complexity IP cores (serial interface and memory), overemphasizing the NI influence. In real IP cores, as the R8-OCP, the area difference between models is minimal.

To compute the deliver time to transmit data a new simulations scenario created: (i) 16-bit flit width; (ii) 8-flit queues depth; (iii) XY routing algorithm; (iv) 5x5 mesh topology. The simulations assume a traffic generator connected to each router. To evaluate the communication models the following parameters are allowed to vary: (i) number of words to be transmitted: 100, 1,000 and 10,000 words; (ii) generated traffic: 3 distinct traffic kinds are generated by randomly varying the source-destination pairs.

Table 1 illustrates the performance for each communication model, considering different numbers of words to be transmitted (each value in the table represents the average value over three simulations, in clock cycles).

Table 1 - Comparison of communication models for different number of words to be transmitted.

Communication Model	Number transmitted words		
	100,000	1,000,000	10,000,000
NORMA	51,833	599,791	6,096,062
NUMA	270,315	2,802,109	29,046,914

Considering the total time of clock cycles to transmit all the data, the NORMA communication model is in average five times faster than the NUMA model. The difference between the two models is on the way they transmit data.

The NORMA model allows a set of data to be grouped in a single packet. In the simulations presented in Table 1, data was always grouped in 1000 packets. For example, in order to transmit 100,000 words 1,000 packets with 100 words were transmitted, each IP transmitting 40 packets (25 IPs).

Because the NUMA model does not easily allow burst transmission, it is necessary to send 100,000 packets with one word, each IP transmitting 4,000 words. The advantage of sending small packets is the reduction in the number of blockings on the network, resulting in the reduction of the packet delivery time. However, with small packets the execution of the arbitration/routing is more frequent, resulting in a considerable overhead, adding to the total time to deliver all packets. This explains the differences observed in Table 1.

These results indicate that, in order to obtain the performance that a communication structure such as a NoC can provide, the communication model should be based in message exchange models such as NORMA. It is no wonder that this is the preferred model in computer and/or telecommunication networks. The advantage of using NUMA models is that they are readily compatible with shared bus architectures, contributing to reusability and the use of legacy IP cores. However, the performance penalty incurred by this choice has to be carefully considered.

6. Conclusions

This paper is concerned with an important issue for the use of NoCs: "What is the communication model that adapts better to NoCs?"

The NUMA model simplifies the wrappers on the IP cores side because their function is only to generate OCP transactions. At the NORMA model, the complexity of wrappers on the IP cores side is higher because they must explicitly create the packets that will be transferred through the network, besides generating the OCP transactions.

In the NUMA model there are only read and write operations transmitted in small packets, which increases the frequency of execution of the arbitration/routing, resulting in an important overhead in the total time to deliver messages. In the NORMA model, the message exchange between IP cores is more flexible and is defined by a service specified at the payload. This flexibility allows the NoC resources to be better explored, providing enhanced performance when compared to the NUMA model.

7. References

[1] Benini, L. De Micheli,G. *Networks on chips: a new SoC paradigm*. IEEE Computer, v.35(1), Jan. 2002, pp. 70-78.

[2] Moraes, F. G.; et al. *HERMES: an Infrastructure for Low Area Overhead Packet-switching Networks on Chip*. Integration: the VLSI Journal, v. 38(1), 2004, pp. 69-93.

[3] Liu, J.; et al.. *Interconnect intellectual property for network-on-chip (NoC)*, Jornal of Systems Architecture, v.50(1), pp. 65-79, 2004.

[4] Bertozzi, D.; Benini, L. *Xpipes: A Network-on-Chip Architecture for Gigascale Systems-on-Chip*. IEEE Circuits and Systems Magazine, v.4(2), pp. 18-31, 2004.

[5] Rãdulescu, A.; et al. K. *An Efficient On-Chip NI Offering Guaranteed Services, Shared-Memory Abstraction, and Flexible Network Configuration*. IEEE Transactions on Computer-aided Design of Integrated Circuits and Systems, v.24(1), pp. 4- 17, 2005.

[6] Ost, L. C.; Mello, A. V.; Palma, J. C. S.; Moraes, F. G.; Calazans, N. L. V. *MAIA - A Framework for Networks on Chip Generation and Verification*. In: ASP-DAC´2005.

[7] OCP-IP. *Open Core Protocol Specification*. Versão 1.0. http://www.ocpip.org/.

[8] Kumar, S. *On Packet Switched Network for Chip Communication*. In: Axel Jantsch and Hannu Tenhunen, editors, Networks on Chip, chapter 5, Kluwer Academic Publishers, 2003, pp. 85-106.