

Performance Evaluation of Wireless Networks on Chip Architectures

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Abstract

The performance benefits of conventional Network-on-Chip (NoC) architectures are limited by the high latency and energy dissipation in long distance multihop communication between embedded cores. To alleviate these problems, wireless on-chip networks are envisioned. Using miniaturized on-chip antennas as an enabling technology, wireless NoCs (WiNoCs) can be designed. In this paper we elaborate on the design methodology and technology requirements for a WiNoC and evaluate its performance. It is demonstrated that a WiNoC outperforms its wireline counterpart in terms of network throughput and latency, and that energy dissipation improves by an order of magnitude.

Keywords

Network on Chip, Wireless communication, Antenna

1. Introduction

The Network-on-Chip (NoC) paradigm has emerged as an enabling methodology to design multi-core chips [1]. In spite of all its advantages, traditional NoCs employ multi-hop communication, wherein the data transfer between two far away blocks gives rise to high latency and energy dissipation. With technology scaling these issues are predicted to become worse in future. To alleviate the problems of high latency and energy dissipation in a NoC, different alternative options have been envisioned. The conventional two dimensional (2D) integrated circuit (IC) has limited floor-planning choices, and consequently it limits the performance enhancements arising out of NoC architectures. 3D NoC architectures combine the benefits of the two new technologies, viz. 3D ICs and NoCs, to offer unprecedented performance gains in terms of latency, throughput and energy dissipation [2]. Photonic NoCs are predicted to provide ultra-high throughput with minimum latency and lower energy dissipation enabled by advances in nanoscale silicon photonics [3]. Low latency communication in a NoC is also shown to be achieved through RF interconnects, where exchange of data between the embedded cores is guided through on-chip transmission lines [4]. All these emerging methodologies need further and more extensive investigation to determine their suitability for replacing and/or augmenting existing metal/dielectric-based planar NoC architectures. Due to increased power density on a smaller footprint, heat

dissipation is a concern with 3D NoCs. Photonic NoCs require extensive layout of optical waveguides and on-chip integrated photonic devices, which are non-trivial technological challenges. To sustain high throughput, RF-interconnect based NoCs require multiple very high frequency oscillators and filters. Consequently it is important to explore further alternative strategies to address the limitations of planar metal interconnect-based NoCs. On-chip wireless communication is a step towards this direction. Over the last few years there have been considerable efforts in the design and fabrication of on-chip miniature antennas operating in the range of tens of gigahertz to hundreds of terahertz, opening up the possibility of designing on-chip wireless links [5-6]. Recent research has uncovered excellent emission and absorption characteristics leading to dipole like radiation behavior in carbon nanotubes (CNTs), making them promising for use as on-chip antennas for wireless communication [6]. In this paper the design principles of Wireless Network-on-Chip (WiNoC) architectures are presented. The performance benefits of these WiNoCs due to utilization of high-speed wireless links are evaluated through cycle accurate simulations. On-chip wireless communication links enable one-hop data transfer between highly separated nodes and hence reduce the hop counts in inter-core communication. In addition to reducing interconnect delay; eliminating multi-hop long distance wireline communication reduces energy dissipation as well. The WiNoCs considered in this work are shown to dissipate significantly less energy compared to traditional wireline NoCs along with notable improvements in throughput and latency.

2. Related work

There has been some effort to provide alternatives to metal/dielectric-based planar interconnect infrastructures for multi-core chips through 3D integration, optical communication and RF interconnects [2-4].

The possibility of on-chip wireless interconnects was demonstrated first in [7] for distributing clock signals. Recently design of a wireless NoC based on CMOS Ultra Wideband (UWB) technology was proposed [8]. It achieves 1 mm transmission range with antennas of length 2.98 mm. Consequently this architecture essentially requires multi-hop communication through wireless channels. The authors principally implemented a synchronous and distributed

medium access control (SD-MAC) protocol for their wireless NoC. This implementation achieves a peak bandwidth of 10 Gbps on a single channel for a system consisting of 16 embedded cores in the 0.18 μm technology node. With the advent of nanoscale antennas based on carbon nanotubes (CNTs) an on-chip wireless interconnection network using optical frequencies can be built for inter-core communications [9-10]. In this paper, we attempt to lay the ground work for the development of an on-chip wireless communication network infrastructure to efficiently enable massive levels of device integration.

3. Wireless NoC

In a generic wireline NoC the constituent embedded cores communicate via switches [1]. Creating a wireless NoC requires substituting wireless links for all or some of the traditional interswitch wireline paths. Below we elaborate the essential components of a WiNoC.

3.1 Wireless NoC Topologies

In spite of all its advantages, a performance limitation in a traditional NoC arises from the planar metal interconnect-based multi-hop communications, which causes high latency and energy dissipation in data transfer between two distant blocks. These problems can be simultaneously resolved if all or some of the wireline links in a NoC are replaced by high-bandwidth single-hop wireless channels. The average path length of any network increases with increase in system size. Consequently we propose to divide the whole system into multiple small clusters of neighboring cores and call these smaller networks *subnets*. As subnets are smaller networks, *intra-subnet* communication will require shorter average path length than a single NoC encompassing the whole system. *Inter-subnet* communication will be achieved through the wireless links, while the intra-subnet communication is still wireline. In principle we propose hybrid wireline/wireless NoC architectures. Each subnet is equipped with a wireless base station (WB), which is capable of transmitting and receiving data packets over the wireless channels. All cores in a subnet are connected to their WB via direct wireline links. When a packet needs to be transferred to a core in a different subnet it travels from the source to its respective WB and reaches the WB of the destination subnet via the wireless channel where it is then routed to the final destination core. For both inter-subnet and intra-subnet data transmission wormhole routing is adopted where data packets are broken down into smaller parts called flow control units or *flits*. Fig. 1 depicts the configuration of a hybrid wireline/wireless NoC with four subnets. In this work we have considered two different subnet architectures, which are discussed below.

3.1.1 Mesh

In this topology the cores in a subnet are interconnected among themselves by a wireline mesh network. This mesh subnet has NoC switches and links as in a standard mesh based NoC. Packet routing within the subnet follows

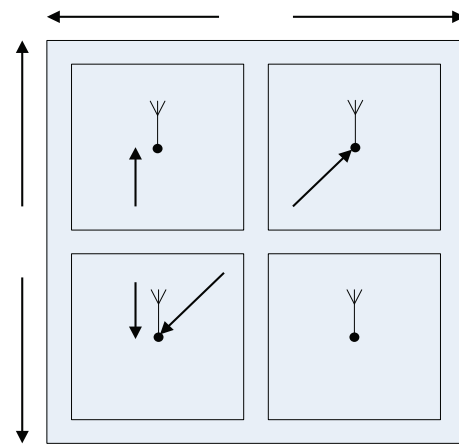


Fig. 1. Hybrid Wireless/Wireline NoC Architecture

dimension order (e-cube) routing. In addition to this underlying mesh all the individual switches have direct wireline links to a WB as shown in Fig. 2 (a).

3.1.2 Hybrid Ring-Star

In this subnet topology all the cores are connected on a ring to two nearest neighbors on either side through conventional wireline NoC switches. In addition there is a central switch which is attached to all the cores as well as the WB as shown in Fig. 2 (b). The central switch provides additional connectivity compared to a simple ring structure. Data routing follows a simple algorithm wherein, if the destination core is within two hops on the ring from the source then the data is routed along the ring. If the destination core is more than two hops away then the data routing takes place via the central switch. Thus within the subnet each core is at a distance of at most two hops from any other core. The central switch is connected to the WB and all inter-subnet packets are routed to the WB from the central switch.

Although only two types of subnet topologies are considered in this work, depending upon application and design choices subnets can have any other regular (or even irregular) topology and a single WiNoC can even have heterogeneous subnets of different architectures.

3.2 On-Chip Antennas

Suitable on-chip antennas are necessary to establish wireless links for WiNoCs. In [5] the authors demonstrated the performance of silicon integrated on-chip antennas for intra- and inter-chip communication. They have primarily used metal zig-zag antennas operating in the range of tens of GHz. Design of an ultra wideband (UWB) antenna for inter- and intra-chip communication is elaborated in [11]. This specific antenna was used in the design of a wireless NoC [8] mentioned earlier in section 2. The above mentioned antennas principally operate in the RF (tens of GHz) range and consequently their sizes are in the order of few millimeters. If the transmission frequencies can be increased to THz/optical range then the corresponding antenna sizes decrease, occupying much less chip real estate. Characteristics of metal antennas operating in the optical and near-infrared region of the spectrum of up to 750 THz have been studied [12]. Antenna characteristics of CNTs in the THz/optical frequency range have also been investigated [9-

10]. Bundles of CNTs are predicted to enhance performance of antenna modules by up to 40dB in radiation efficiency and provide excellent directional properties in far-field patterns [13]. Moreover these antennas can achieve a bandwidth of around 500 GHz, whereas the antennas operating in the RF range achieve a bandwidth of 10's of GHz [13]. Thus antennas operating in the THz/optical frequency range can support much higher data rates. CNTs have several characteristics that make them suitable as on-chip antenna elements for optical frequencies. Given wavelengths of several hundreds of nanometers to several micrometers there is a need for virtually one-dimensional antenna structures for efficient transmission and reception. With diameters of a few nanometers and any length up to a few millimeters possible, CNTs are the perfect candidate. Such thin structures are almost impossible to achieve with traditional microfabrication techniques for metals. Virtually defect free CNT structures do not suffer from power loss due to surface roughness and edge imperfections in traditional metallic antennas. In CNTs, ballistic electron transport leads to quantum conductance, resulting in reduced resistive loss, which allows extremely high current densities in CNTs, namely 4-5 orders of magnitude higher than copper. This enables high transmitted powers from nanotube antennas, crucial for long-range communications. By shining an external laser source on the CNT, radiation characteristics of multi-walled carbon nanotube (MWCNT) antennas are observed to be in excellent quantitative agreement with traditional radio antenna theory [6] although at much higher frequencies of hundreds of THz. Using various lengths of the antenna elements corresponding to different multiples of the wavelengths of the external lasers, scattering and radiation patterns can be improved. Such nanotube antennas could be a potential candidate for establishing on-chip wireless communications links and are hence used in this work. As mentioned above, the NoC is divided into multiple subnets. Hence, the WB in each subnet needs to be equipped with transmitting and receiving antennas, which will be excited using external laser sources. As mentioned in [3] the laser sources can be located off-chip or bonded to the silicon die. As the whole WiNoC is divided into a few subnets, only a

small number of coupling points of the laser with the antennas will be required. The requirements of using external sources to excite the antennas can be eliminated if the electroluminescence phenomenon from a CNT is utilized to design linearly polarized dipole radiation sources [14]. But further investigation is necessary to establish such devices as successful transceivers for on-chip communication. Instead of utilizing the wireless links, optical fibers can be used to establish communication links between the cores [3]. But in that case we need to lay out optical fibers across the whole chip.

To achieve line of sight communication channels between WBs using CNT antennas at optical frequencies, the packaging material of the chip has to be elevated from the substrate surface to create a vacuum for transmission of the high frequency EM waves. Techniques for creating such vacuum packaging are already utilized for MEMS applications [15]. Hence, such techniques in chip packaging can be adopted to make creation of line of sight communication between CNT antennas viable.

3.3 Communication Protocols

In the proposed WiNoC, intra-subnet data routing depends on the topology of the subnets. Inter-subnet data exchange occurs using the wireless channels. We propose to keep the number of subnets small enough so that, by using multiband laser sources to excite CNT antennas, different frequency channels can be assigned to pairs of communicating subnets. This will require using antenna elements tuned to different frequencies for each pair thus creating a form of Frequency Division Multiplexing (FDM). This is possible by using CNTs of different lengths which are multiples of the wavelengths of the carrier frequencies. High directional gains of these antennas demonstrated in [6] [13] aid in creating directed channels between source and destination pairs. The carrier has to be modulated by optical modulators. It is shown in [16] that high-speed silicon integrated Mach-Zehnder optical modulators are currently commercially available. In [17], 24 continuous wave laser sources of different frequencies and modulators operating at the rate of 10Gbps are used. Using such devices and assuming four subnets in our WiNoC architectures as shown in Fig. 1, four different frequency channels each with a data rate of 10Gbps can be created between each of the six pairs (choosing pairs of two subnets among the four possible) of communicating subnets. Thus six parallel wireless channels each with a maximum bandwidth of 40Gbps between any two subnets can be created. At the receiver a Low Noise Amplifier (LNA) can be used to boost the power of the received electrical signal which will then be routed into the destination subnet. As noted in [17] this data rate is expected to increase many fold with technology scaling in future. The modulation scheme adopted is simple On-Off Keying (OOK) and consequently it does not require complex clock recovery and synchronization circuits. As mentioned above each communicating pair can have four different frequency channels. But the flit width in NoCs is generally much more than this. Consequently to send a whole flit through the

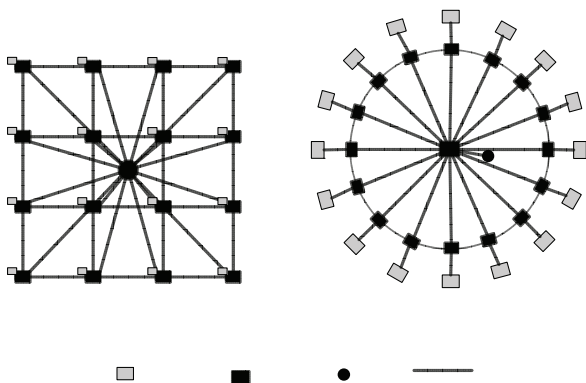


Fig. 2. Subnet architectures (a) Mesh and (b) hybrid ring-star

wireless link using a limited number of distinct frequencies a proper channelization scheme needs to be adopted. In this work we assume a flit width of 32 bits. Hence to send the whole flit using the 4 distinct frequency channels Time Division Multiplexing (TDM) is adopted. As the optical modulators can operate at 10Gbps each time slot in the TDM scheme can be of 0.1ns. The TDM modulator/demodulator is implemented as a part of the WB. Fig. 3 shows the adopted communication mechanism for the inter-subnet data transfer using the wireless channels in the WiNoC.

4. Performance Metrics

To characterize the performance of the proposed WiNoC architectures three network parameters such as latency, throughput and energy dissipation in communication are considered. Latency refers to the length of time in clock cycles, between the injection of a message header at the source node and the reception of the tail flit at the destination. Throughput is defined as the average number of flits successfully received per embedded core per clock cycle. Energy dissipation per packet is the average energy dissipated by a single packet when routed from the source to destination node completely. Both the wireline subnets and the wireless channels contribute to this. For the subnets the sources of energy dissipation are the inter-switch wires and the switch blocks. For the wireless channels the main contribution comes from the WBs, which include antennas, transceiver circuits and other communication modules like the TDM block and the LNA. Energy dissipation per packet, E_{pkt} can be calculated according to the equation below.

$$E_{pkt} = \frac{N_{intrasubnet} E_{subnet,hop} + N_{intersubnet} E_{wi-channel}}{(N_{intrasubnet} + N_{intersubnet})} \quad (1)$$

In (1), $N_{intrasubnet}$ and $N_{intersubnet}$ are the total number of packets routed within the subnet and wireless channels. $E_{subnet,hop}$ is the energy dissipated by a packet traversing a single hop on the wireline subnet including a wireline link and switch and $E_{wi-channel}$ is the energy dissipated by a packet traversing a single hop on the wireless channel.

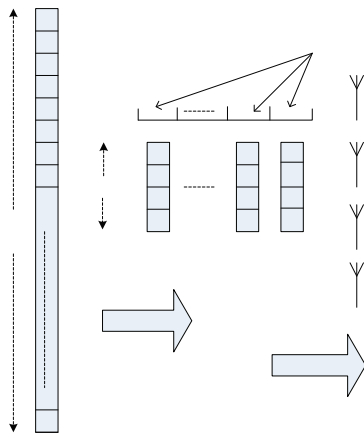


Fig. 3. Adopted communication protocol for the wireless channel

5. Experimental results

In order to evaluate the performance of the proposed WiNoC architectures a 64-core based system on a 20mmx20mm die is considered. As shown in Fig. 1 the whole system is divided into four subnets. The subnets are wireline and they are connected through the wireless channels as explained earlier. Two specific subnet architectures, viz. the mesh and the hybrid ring-star are considered. The performance of the WiNoCs is compared with respect to two completely wireline NoC architectures. One of the wireline architectures is the well known flat mesh. The other wireline architecture considered is the hierarchical mesh. In the hierarchical mesh the whole NoC is divided into four mesh-based smaller subnets. Each switch is connected to the neighboring switches in its own subnet following a regular mesh topology and two more switches in two other subnets as indicated in Fig. 4 where inter-subnet connections for only one switch is shown. This particular topology is considered to show the performance of the proposed WiNoCs against a hierarchical wireline network as those are known to perform better than flat ones. To model the performance of the WiNoC a cycle-accurate network simulator is employed. We assume a self-similar injection process [1]. Uniform spatial traffic distribution is assumed for all architectures. Figs. 5 (a) and (b) show the throughput and latency characteristics of the proposed WiNoCs. These are measured with respect to the traffic injection load, which is defined as the number of flits injected by each core per cycle. It is evident that the WiNoCs outperform both the wireline mesh architectures. There are two reasons for this: first, the wireless links between the subnets reduce the hop counts when communicating between two distant nodes. Packets take fewer hops to reach from source to destination occupying network resources like links or switches for a smaller period of time. Second, although the individual subnets are still wireline, they have less congestion due to their comparatively smaller size. The hierarchical wireline mesh has lower latency and higher throughput compared to the flat mesh as it has extra connectivity from each switch as well as the advantages of smaller subnets. But still its performance is worse than the wireless architectures. This happens because in the hierarchical mesh the wireline communication links between switches in different subnets are still long and therefore require multi-cycle communication.

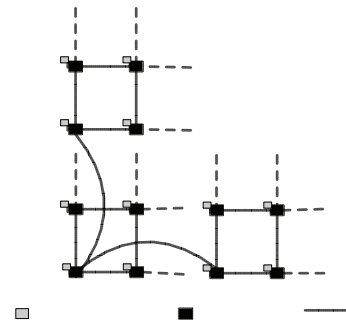


Fig. 4. Hierarchical mesh-based NoC.

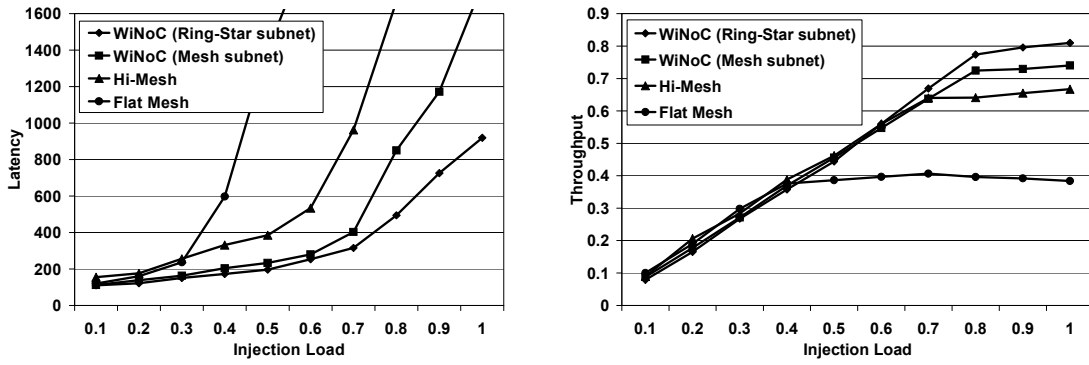


Fig.5. (a) Latency and (b) throughput characteristics of the proposed WiNoC architectures.

To determine the energy dissipation characteristics of the WiNoCs, we first estimated the energy transmitted by the antenna elements. As noted in [6] the directional gain of MWCNT antennas is very high. The ratio of emitted power to incident power is around -5dB along the direction of maximum gain. Assuming an ideal line-of-sight channel over a few millimeters, transmitted power degrades with distance following the inverse square law. Therefore the received power P_R can be related to the transmitted power P_T as

$$P_R = \frac{G_T A_R}{4\pi R^2} P_T \quad (2)$$

In (2), G_T is the transmitter antenna gain which can be assumed to be -5dB [6]. A_R is the area of the receiving antenna and R is the distance between the transmitter and receiver. The area of the receiving antenna can be found by using the antenna configuration used in [6]. It uses a MWCNT of diameter 200nm and length 7λ where λ is the wavelength of the optical frequency used. This particular length was chosen as it was shown to produce highest directional gain at the transmitter, G_T . In one of the setups used in [6] the wavelength of the laser used was 543.5nm and hence the length of the antenna is around $3.8\mu\text{m}$. Using these values of the parameters as mentioned above, a transmitted power of 0.3mW per bit is required to obtain a received power of 1pW which can then be subsequently amplified by state of the art low noise amplifiers (LNA) [18]. As the diagonal wireless links between subnets shown in Fig. 1 are the longest, the power transmitted for those should also be enough for the other rectangular links. For a 20mmx20mm die this distance is therefore 14.14mm. Using these parameters and (2) the power and hence the energy dissipated by the antennas for a pair of communicating subnets can be computed for a single frequency channel. As mentioned earlier in this study 4 different carrier frequencies are assumed between any two communicating subnets. The exact antenna configuration and power dissipation will depend on the frequencies of the carriers. For simplicity we use the antenna power corresponding to one particular wavelength mentioned above to estimate the total power dissipation of 4 such single frequency channels. However in reality based on the exact frequency the parameters G_T , A_R and hence the

transmitted power requirement P_T will vary. Among the other components the energy dissipations of the wireline subnet switches and the WBs are obtained through Synopsys simulation. To estimate the energy dissipation of the WBs only the TDM modulator-demodulator and routing blocks for the wireless channels are synthesized using Synopsys with 65 nm standard cell libraries from CMP [19]. The wireline switches are also synthesized using the same library. Among the rest of the components of the WB, the energy dissipation of the antennas is estimated as elaborated above, and that of the MZM optical modulator/demodulator is obtained from [16]. The energy dissipation of the low noise amplifier is obtained following the design in [18]. The energy dissipated by the wireline links of the subnets depend on their length, which depend on the topology. The capacitance of each wireline link and subsequently its energy dissipation was obtained through HSPICE simulations taking into account the specific layout for each topology. Using these values the average energy dissipation for each of the architectures considered here can be computed according to (1). Fig. 6 shows the average energy dissipation per packet for the two WiNoC architectures proposed in this paper along with the reference wireline mesh and hybrid mesh. The packet size was considered to be of 64 flits. As can be seen from the plot the wireline mesh architectures dissipate over an order of magnitude more energy than either of the WiNoCs. This huge savings can be attributed to elimination of long distance wireline communication. Lower latency in the WiNoCs also signifies that each bit occupies fewer resources within the

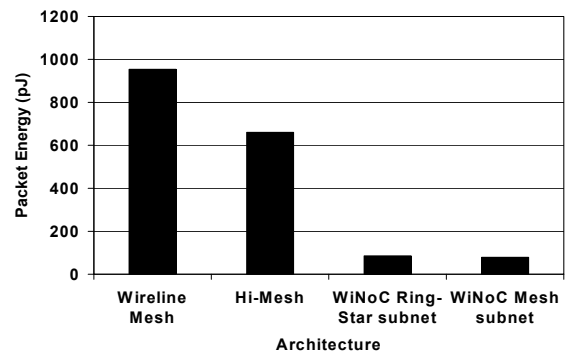


Fig. 6. Energy dissipation per packet at network saturation.

network consequently dissipating less energy. As all the WiNoCs can support different data bandwidths, a metric for fair comparison can be bandwidth per unit energy. The achievable bandwidth per unit energy is 2.58Gbps/pJ and 6.20Gbps/pJ for the wireline mesh and the hierarchical mesh respectively. The wireless architectures are capable of achieving much higher bandwidths per unit energy, namely 71.45Gbps/pJ and 72.26Gbps/pJ, for the Ring-Star and the Mesh subnet topologies respectively.

6. Conclusions and future work

In this paper we show that the problems of high latency and energy dissipation in conventional NoCs can be resolved by establishing high-bandwidth single-hop wireless channels to replace long distance wireline links. Design principles of a wireless NoC are elaborated. It is shown to outperform corresponding wireline implementations.

In ongoing and future investigations, performance benefits of various on-chip wireless network architectures and the role of improved modulation and channelization schemes along with different on-chip antennas will be studied.

7. Acknowledgements

Benjamin Belzer's work was partially supported by NSF grant CCF-0635390. Alireza Nojeh's work was partially supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada

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