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Exploiting antenna directivity in wireless NoC architectures

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ABSTRACT

Wireless Network-on-Chip (WiNoC) is an emerging on-chip communication paradigm and a candidate solution for dealing with the scalability problems which affect current and next generation many-core architectures. In a WiNoC, the transceivers that allow the conversion between electrical and radio signals, account for a significant fraction of the total communication energy budget. In particular, the transmitting power for wireless communications is strongly affected by the orientation of the antennas. This paper studies the impact of antennas orientation on energy figures of a WiNoC architecture and performs a design space exploration for determining the optimal orientation of the antennas in such a way to minimize the communication energy consumption. Experiments have been carried out on state-of-the-art WiNoC topologies, on both synthetic and real traffic scenarios, and validated by means of a commercial field solver simulator. When the antennas are optimally oriented, up to 80% energy saving (as compared to the case in which antennas have all the same orientation) has been observed.

1. Introduction

Accordingly to the predictions of the International Technology Roadmap for Semiconductors, the number of integrated processing elements into a modern multiprocessors system-on-chip (MPSoC) is increasing dramatically [1]. It is foreseen that the threshold of 1,000 processing cores will be surpassed by the year 2020. A practical demonstration of such a trend can be observed by considering two prototypes developed by Intel [2,3]. The first one, developed in 2008, integrates 80 processing cores in a 65 nm CMOS technology, while the second one, developed after 5 years, integrates 256 cores in a 22 nm Tri-Gate CMOS technology. As the number of communicating cores increases, the role played by the on-chip communication system becomes more and more important. Both the above prototypes use a Network-on-Chip (NoC) as interconnection fabric. In fact, the NoC paradigm is considered as the most viable solution for addressing the communication issues in the context of many-core architectures [4].

Unfortunately, due to their multi-hop nature, as the network size increases, conventional NoCs which use electric point-to-point links, start to suffer from scalability problems, both in terms of communication latency and energy. For facing with such scalability issues, several emerging interconnect paradigms such as Optical, 3D, and RF solutions have been proposed [5]. In particular, a specific class of RF interconnect introduces a wireless backbone upon traditional wire-based NoC substrate [6].

The use of the radio medium for on-chip communication is enabled by means of antennas and transceivers which form the core of a *radio-hub*. A radio-hub augments the communication capabilities of a conventional NoC switch/router by allowing it to wireless communicate with other radio-hubs in a single hop. The reduction of the average communication hop count, has a positive impact on both performance and power metrics but, the price to pay, regards the silicon area due for transceivers and antennas. Another aspect regards the attenuation introduced by the wireless channel. Since electromagnetic waves are propagated in lossy silicon, the power due to the wireless signaling represent an important contribution of the entire communication energy budget. In fact, in [7] it has been shown that the transmitter is responsible for about 65% of the overall transceiver power consumption, while in [8] such contribution is more than 74%. Thus, wireless communication results more energy efficient than wired communication when the communicating nodes are far away each other (in several studies such a distance has been reported being greater than two hops).

With regards to the amount of transmitting power needed to guarantee a certain reliability level (usually measured in terms of bit error rate), a common practice is computing the worst case attenuation and transmitting using such maximum power level irrespective of the location of the destination. Furthermore, in the

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current WiNoC literature, the radiation pattern of the antenna is considered isotropic, that is, it is assumed that the antenna exhibits the same behavior irrespective of the transmitting/receiving directions. However, it is well known from antennas theory that the behavior of the antenna strongly depends on the direction from/to which the signal is received/transmitted. Such behavior is described by a fundamental antenna parameter, namely, *antenna directivity*, which describes the variation of the transmitting/receiving signal intensity for different observation angles. The directivity effects, widely studied in the context of free space communications, have been recently investigated in the context of intra-chip communications [9]. In the context of WiNoCs, however, there are no works in literature that take into account the directivity effects, and the antenna orientation is left out from the set of design parameters to be explored.

In this paper, we analyze the impact of antennas orientation on energy metrics in WiNoC architectures. Based on such analysis, we formulate the problem of finding the antennas orientation in such a way to minimize the total communication energy in the following two cases. The case in which the information about the applications that will be mapped on the WiNoC and their communication characteristics are not known, and the case in which they are known at design time. We refer to the first case as *general purpose* and the second one as *application specific*. Further, we also formulate the problem of finding the antennas orientation in such a way to minimize the transmitting power for the worst case. This latter problem is important in the case in which the WiNoC does not implement any technique for dynamic transmitting power calibration [10,11] and when the same transmitting power is used for any communicating pairs irrespective of their position into the WiNoC. Experiments, carried out on state-of-the-art WiNoC architecture, namely, HmWNoC [12] show that important energy saving, up to 80% can be obtained by properly set the orientation of the antennas.

2. Related Work

The capability of MOS transistors of operating at frequencies as high as tens of GHz [13] makes it possible the development of fully integrated RF systems comprising integrated antennas and transceivers. In fact, as the frequency increases, dimensions of typical RF devices, such as antennas and inductors, decrease. For example, an antenna operating at 60 GHz can be as small as 680 μm in terms of axial length. Based on this, several research groups have experimentally proven the feasibility of inter- and intra-chip communication by using existing CMOS processes [9,14–16]. In particular, in the study conducted in [9], in which an experimental setup based on a test chip has been used, it has been shown that propagation mechanism in lossy silicon is based, mainly, on the propagation of surface waves. In the same work, the effects of metal structures and the contribution of antenna orientation has been investigated.

Wireless Network-on-Chip (WiNoC) paradigm has been recently proposed as a CMOS compatible solution [17] for addressing the scalability problems affecting the on-chip communication system for future many-core architectures. Several WiNoC architectures have been proposed in literature [12,18,19]. Since transceivers and antennas consume a relevant fraction of the total silicon area, in [12] the authors introduce several criteria to establish the optimum number of wireless interfaces under performance constraints. In the same work, a new architecture named *HmWNoC* has been presented. Such architecture exploits the *small-world* property [20] in which the network is divided in subnets and in which wireless and wire-line shortcuts can be used for inter-subnet communications. More recently, the same authors study the impact of various modulation schemes in terms of silicon area and energy efficiency [19].

Other interesting WiNoC alternatives can be found in [21] and in [22]. In particular, the former proposes a wireless 3D NoC architecture which uses inductive coupling for inter-layer communication, while the latter introduces antennas based on graphene. Graphene-based antenna assures working frequency in the Terahertz band while utilizing lower chip area for antennas as compared to the metallic counterparts.

3. Background

Given a transmitting and a receiving antenna, this section provides the background on how computing the minimum transmitting power which guarantees a certain data rate and a maximum bit error rate (BER).

3.1. Signal Strength Requirements

For adapting the baseband signal to the wireless medium, the most used modulation scheme in the WiNoC context is Amplitude Shift Keying or On Off Keying (ASK-OOK) [12,18,19]. The reliability of the ASK-OOK modulation (in terms of BER) is related to the energy spent per bit, E_{bit}, as follows:

$$BER = Q\left(\sqrt{\frac{E_{bit}}{N_0}}\right), \tag{1}$$

where N_0 is the transceiver noise spectral density (noise introduced by the transceiver) and the Q function is the tail probability of the standard normal distribution which is defined in Eq. (2).

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{y^2}{2}} dy \tag{2}$$

Since $E_{bit} = P_r/R_b$, where P_r is the power received at the terminal of the receiver antenna while R_b is the data rate, the required transmitting power for a given data rate and BER requirement and for a given transceiver's thermal noise can be computed as:

$$P_r = E_{bit} \cdot R_b = \left[Q^{-1}(BER)\right]^2 N_0 R_b, \tag{3}$$

where Q^{-1} is the inverse of the Q function. Thus, the minimum transmitting power needed for reaching the receiving antenna can be computed as:

$$P_t = P_r/G_a, \tag{4}$$

where, P_r is given by Eq. (3) and G_a is the attenuation introduced by the wireless medium ($G_a < 1$). The next subsection describes how the attenuation G_a can be computed.

3.2. Wireless Medium Attenuation

As discussed in the previous subsection, the required transmitting power depends on several factors, including, the type of modulation, the transceiver noise figure, and the attenuation introduced by the wireless medium. Let us consider Fig. 1 which shows a transmitting antenna with an output power P_t and a relative angle respect the receiving antenna of (θ_t, ϕ_t), and a receiving antenna, located at distance R, with a relative angle respect the transmitting antenna of (θ_r, ϕ_r). The fraction of the transmitting power that reaches the terminal of the receiving antenna, P_r, can be computed by means of the Friis transmission equation [23] valid when $R > 2D^2/\lambda$, where D is the maximum dimension of antenna (axial length in the considered case) and λ is the wavelength[1]. The Friis

[1] For a zigzag antenna operating at 60 GHz, which has an axial length of 680 μm, the Friis equation is valid only if the distance R between two generic antennas is at least equal to $R_{MIN} = 0.18$ mm. The latter is obtained considering that in a silicon substrate the wavelength is about $\lambda = 5.02$ mm (in the range of millimeter waves).