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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 1000 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).

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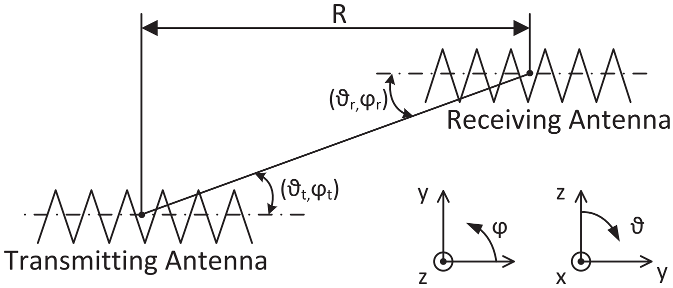

Fig. 1. Friis transmission equation: geometrical orientation of transmitting and receiving antennas. As indicated, considering a spherical coordinate system, ϕ is the azimuthal angle in the XY plane, where the X-axis is 0° and Y-axis is 90°. θ is the elevation angle where the Z-axis is 0°, and the XY plane is 90°.

transmission equation is:

$$G_a = \frac{P_r}{P_t} = e_t e_r \frac{\lambda^2 D_t(\theta_t, \phi_t) D_r(\theta_r, \phi_r)}{(4\pi R)^2}, \tag{5}$$

where:

- e_t and e_r are the efficiencies of the transmitting and receiving antenna, respectively. These parameters mainly represent the signal losses in the silicon substrate. For reducing such contribution, high resistivity Silicon on Insulator (SoI) substrates (> 1 KΩcm) can be used [24] or a polyamide stratus (few micron thick) can be inserted under the antenna [25].
- D_t and D_r are the directivities of the transmitting and receiving antenna, respectively. They quantify how much better the antenna can transmit or receive in a specific direction.
- λ is the effective wavelength. For an IC substrate, it is estimated by using the material properties of the top IC layers (silicon dioxide $\epsilon_r = 3.9$) [26].

Eq. (5) highlights the parameters which determine the gain G_a and represents a first order model of the wireless channel. In fact, second order effects such as, polarization matching, wave reflections, and multi-path effects are not modeled by Eq. (5). However, in practical cases, G_a computation is estimated by means of Eq. (6)

$$G_a = \frac{P_r}{P_t} = \frac{|S_{12}|}{(1 - |S_{11}|)(1 - |S_{22}|)}, \tag{6}$$

where, S_{11}, S_{12}, and S_{22} are the scattering parameters. Such parameters are gathered by using field solver simulation tools [14] or by direct measures from realized prototypes.

4. Antenna directivity optimization

4.1. Antenna directivity

As described by Eq. (5), the attenuation introduced by the wireless medium, strongly depends on the directivity function. Based on this, the orientation of the antennas in a WiNoC represents an interesting parameter to be explored.

The energy consumed by a wireless communication between a given transmitter and receiver pair, depends on their reciprocal location and orientations. Specifically, the energy consumed for wirelessly transmitting a bit of information from transmitter i to receiver j is:

$$E^{tx}_{ij} = \frac{P_{t_{ij}}}{\eta R_b}, \tag{7}$$

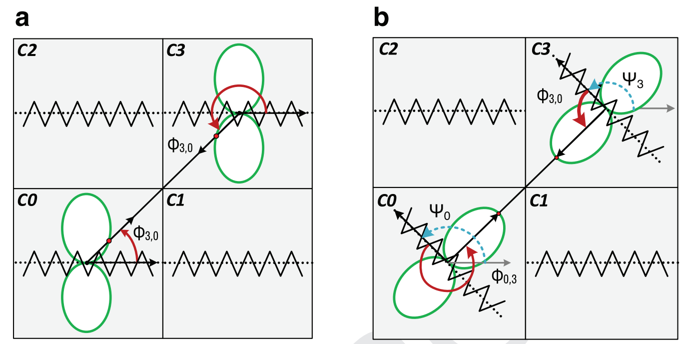

Fig. 2. Reciprocal antennas orientation and directivity functions. The directivity between C0 and C3 improves from configuration (a) to configuration (b).

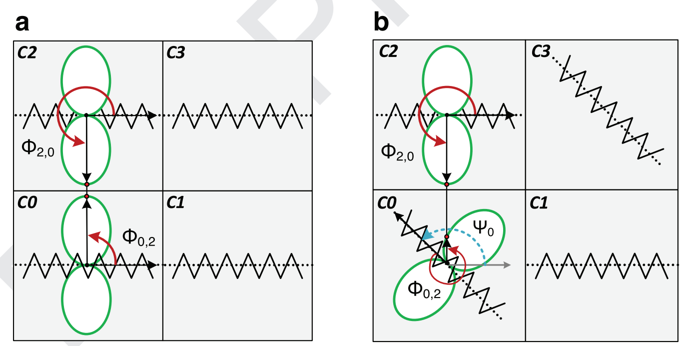

Fig. 3. Reciprocal antennas orientation and directivity functions. Configuration (a) improves communication energy between tiles C0 and C2 whereas configuration (b) improves communication energy between tiles C0 and C3.

where η is the transmitter efficiency. Considering Eqs. (4) and (5), the Eq. (7) can be written as:

$$E^{tx}_{ij} = \frac{P_r / D_t(\Phi_{ij}) D_r(\Phi_{ji}) \left(\frac{\lambda}{2\pi R_{ij}}\right)^2}{\eta R_b}. \tag{8}$$

Let ψ_i and ψ_j be a rotation of antenna i and antenna j as respect to the die plane, respectively. Thus, Eq. (8) normalized by the constant terms can be written as:

$$\overline{E^{tx}_{ij}} = \frac{R^2_{ij}}{D_t(\Phi_{ij} - \psi_i) D_r(\Phi_{ji} - \psi_j)}. \tag{9}$$

Thus, for minimizing the communication energy from i to j, it needs to determine a rotation ψ_i and a rotation ψ_j such that Eq. (9) is minimized.

For the sake of example, let us consider Fig. 2(a) in which four antennas and their reciprocal orientations in the die plane are shown. The energy consumption of the communication between tiles C0 and C3 can be minimized by maximizing the directivity of their respective antennas. This is obtained by rotating the antennas in tiles C0 and C3 by the angles ψ_0 and ψ_3, respectively, as shown in Fig. 2(b).

It should be pointed out that, selecting a certain antenna orientation for improving the energy efficiency of a given transmitter/receiver pair, might negatively affects the energy figures of other transmitter/receiver pairs. For instance, the directivity of the antennas in tiles C0 and C2 before the rotation is maximized [see Fig. 3(a)] and thus, their communication energy is minimized. However, after the rotation of the antennas in tiles C0 and C3 [see Fig. 3(b)], although the communication energy between C0 and C3 improves, that between C0 and C2 worsens.

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4.2. Formulation of the problem

Based on the above considerations, this subsection formulates the problem of minimizing the wireless communication energy by means of antennas orientation optimization. Specifically, three scenarios, namely, *application specific*, *general purpose*, and *worst case* scenarios will be analyzed.

4.2.1. Application specific scenario

In the *application specific scenario* it is assumed that communication traffic information is available at design time. Let V_{ij} be the traffic volume (in bits) from radio hub i to radio hub j. Let $E_{ij}(\Psi)$ be the energy consumption for transmitting one bit from radio hub i to radio hub j when the antennas are oriented based the orientation vector Ψ. The ith component of Ψ represents the orientation of the antenna of radio hub i. $E_{ij}(\Psi)$ is computed by Eq. (9). The total normalized wireless communication energy can be computed as:

$$E_{tot}^{(as)}(\Psi) = \sum_{i=0}^{N}\sum_{j=0}^{N} V_{ij} \times E_{ij}(\Psi). \tag{10}$$

Thus, the problem of minimizing the wireless communication energy, by means of antennas orientation optimization, for the application specific scenario can be formulated as finding the antennas orientation vector Ψ which minimizes $E_{tot}^{(as)}(\Psi)$.

4.2.2. General purpose scenario

In the *general purpose scenario* it is assumed that communication traffic information is not available at design time. Based on this, the same traffic volume for each communicating pair is assumed. The total wireless communication energy per bit can be computed as:

$$E_{tot}^{(gp)}(\Psi) = \sum_{i=0}^{N}\sum_{j=0}^{N} E_{ij}(\Psi). \tag{11}$$

Thus, the problem of minimizing the wireless communication energy, by means of antennas orientation optimization, for the general purpose scenario can be formulated as finding the antennas orientation vector Ψ which minimizes $E_{tot}^{(gp)}(\Psi)$.

4.2.3. Worst case scenario

Please notice that, in the above two scenarios (application specific and general purpose), it is assumed that the transceiver implements a transmitting power calibration technique (*e.g.*, [10,11]) which allows the transmitting radio hub to use the minimum transmitting power to reach the destination guaranteeing a certain bit error rate.

In WiNoCs in which the power amplifier (PA) in the transceivers does not implement any transmitting power modulation mechanism, the PA is configured to use the maximum transmitting power irrespective of the recipient of the transmission. We refer to this case as *worst case* scenario. In this case, the total wireless energy consumption per bit is determined by the maximum $E_{ij}(\Psi)$:

$$E_{tot}^{(wc)}(\Psi) = \max_{i,j=1,\ldots,N} E_{ij}(\Psi). \tag{12}$$

Thus, the problem of minimizing the wireless communication energy, by means of antennas orientation optimization, for the worst case scenario can be formulated as finding the antennas orientation vector Ψ which minimizes $E_{tot}^{(wc)}(\Psi)$.

4.3. General design flow

The Friis equation used in the problem formulation is not suitable for computing the actual attenuation of the wireless medium. In fact, it models only first order effects which are however enough for early design space exploration. Thus, the use of accurate field solver simulators or direct measurements on real prototypes are needed for implement the overall optimization flow. The basic steps which form the design flow can be summarized as follows.

1. Compute the radiation pattern of the antenna by means of a field solver simulator or by test-chip measurements. The radiation pattern represents the term D in Eq. (8).
2. Explore the antennas orientations design space for determining the optimal antennas orientations which minimize the total communication energy (*cf.*, Subsection 4.2).
3. Configure the antennas with the orientations found in the previous step and compute the actual attenuation by means of a field solver simulators for determining the transmitting power for each antennas pair. Let $P_{t_{ij}}$ be the transmitting power for communication from antenna i to antenna j.
4. For the general purpose and application specific scenarios, use the $P_{t_{ij}}$ computed in the previous step for configuring the variable gain amplifier controller [10,11]. For the worst case scenario, set the transmitting power of every transmitter to $\max P_{t_{ij}}$.
5. After that the antenna shapes has been drawn by means of a standard layout CAD tool (selecting a specific metal layer), apply a rotation of the drawn objects in accordance with the optimization results.

In the next section, such design flow is applied for designing energy efficient WiNoC configurations for the different scenarios, under different traffic patterns and different parameters.

5. Experimental results

In this section we explore the design space spanned by the orientations of the antennas in a WiNoC architecture with the goal of improving its energy efficiency.

5.1. Simulation methodology

Given the non-linear, high dimensional, multi-modal, and non-smooth nature of $E_{ij}(\Psi)$, the optimization problems Eqs. (13)–(15), defined in the previous section, have been solved by means of simulated annealing.

$$\min_{\Psi} \sum_{i=0}^{N}\sum_{j=0}^{N} V_{ij} \times E_{ij}(\Psi) \tag{13}$$

$$\min_{\Psi} \sum_{i=0}^{N}\sum_{j=0}^{N} E_{ij}(\Psi) \tag{14}$$

$$\min_{\Psi} \max_{i,j=1,\ldots,N} E_{ij}(\Psi) \tag{15}$$

Specifically, we have chosen the geometric annealing schedule [27] as it is the most used and recommended one. The geometric annealing temperature schedule defines the temperature at iteration i as $T = T_0 q^{\lfloor \frac{i}{L} \rfloor}$, where T_0 is the initial temperature and L is the number of iterations per temperature level and q is the geometric progression ratio to 0.9. In the experiments, the initial and final temperatures have been set to 1 and 0.001, respectively. The maximum number of iterations, L, is set to $(N \times |\Psi|)^2$. The antenna orientations are randomly generated, from the current configuration, by interchanging two antennas, or by modifying the orientation of an antenna.

For each of the above scenarios, namely, application specific AS, Eq. (13), general purpose GP, Eq. (14), and worst case WC,

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Table 1
HFSS setup parameters.

Parameter	Value
Chip size	20 mm × 20 mm
Technology	28 nm˜SOI
Silicon resistivity	$\rho = 5$ KΩcm
Substrate thickness	350 μm
Oxide (SiO_2) thickness	30 μm
Antenna elevation	2 μm
Antenna thickness	2 μm
Antenna axial length	2 × 340 μm
Operation frequency	60 GHz
Absolute bandwidth	16 GHz

Eq. (15), the optimal set of antennas orientation, namely, $\Psi_{opt}^{(AS)}$, $\Psi_{opt}^{(GP)}$, and $\Psi_{opt}^{(WC)}$, are simulated by means of an accurate field solver simulator for obtaining the scattering parameters. Then, scattering parameters are used by Eq. (6) for computing the transmitting power for each transmit–receive antenna pair. Such transmitting power data are then used for back-annotating a cycle accurate WiNoC simulator [28] for determining the total energy figures under different traffic scenarios.

In all the experiments we consider a zigzag antenna modeled and characterized with Ansoft HFSS [29] (High Frequency Structural Simulator). HFSS produces scattering parameter and radiation pattern as output. Table 1 reports the simulation parameters used in all the experiments. The selection of the chip size has been carried out in accordance with the International Technology Roadmap for Semiconductors (ITRS) [30] predictions on high-end MPSoCs.

Fig. 4 shows the antenna directivity, by means of its radiation pattern, considering the direction of maximum radiation under the substrate ($\phi = 100^{\circ}$).

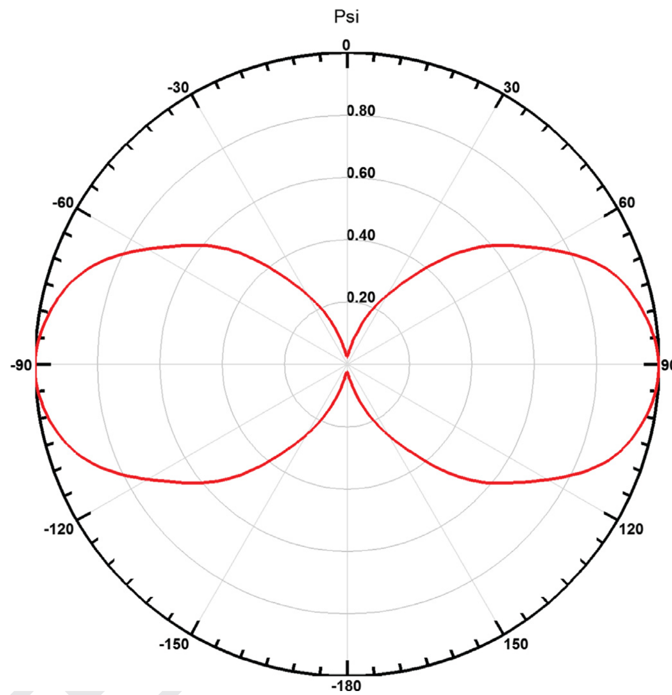

Fig. 4. Radiation pattern for a zigzag antenna at the elevation of maximum radiation ($\phi = 100^{\circ}$). $\theta = 0^{\circ}$ is the direction orthogonal to the antenna's main axis. According to Fig. 1, we assume the antenna situated upon the XY plane (coplanar with silicon die).

5.2. Energy saving analysis

Let us know analyze the energy savings in the application specific (AS), general purpose (GP), and worst case (WC) scenarios. As communication traffic patterns, we used a set of representative applications of SPLASH-2 and PARSEC benchmarks suites. Such benchmarks have been executed on Graphite Multi-core Simulator [31] and the communication topology graphs and communication volumes information have been extracted. In all the experiments, the baseline WiNoC architecture is msWiNoC [12] in which all the antennas have the same orientation. In the case of AS and GP, it is assumed that the power amplifier in the transceivers is equipped with the reconfigurable variable gain amplifier (R-VGA) module [10] with seven power steps. The estimated transmitting power ranges from 8 µW (−21 dBm) to 794 µW (−1 dBm), that in terms of energy per bit correspond to 0.42 pJ/bit and 1.4 pJ/bit, respectively. Based on this, we have selected seven equally spaced power steps into such range. That is, the ith power step corresponds to a transmitting power of $8 + (i-1) * 786/6$ µW.

Fig. 5 shows the percentage energy saving when the antennas are optimally oriented based on the solutions of optimization problems Eqs. (13)–(15) considering four antenna orientations steps. On average, up to 89%, 82%, and 78% energy saving is observed for AS, GP, and WC scenario, respectively.

Fig. 6 shows the percentage energy saving when the number of radio hubs is made to vary. As expected, the energy saving increases as the number of radio hubs increases due to the fact that more communications make use of the radio medium. However, no relevant improvement is observed when the number of radio hub is greater than eight. Such trend is related to the network size that in our experiments consists of 256 communicating cores. In fact, for such a medium network size, eight radio hubs are enough for drastically reducing the average hop count. Above eight radio hubs, the short distances between them, makes more suitable performing the communication by means of the wired underlying NoC. Please remind that, wireless transmissions becomes effective in term of energy efficiency when the path length is greater than three hops [8].

We analyzed four cases in which 2, 4, 8, and 16 orientations are allowed. Such allowed orientations are those obtained by equally dividing the orientations from 0° to 180° into 2, 4, 8, and 16 angles, respectively. Fig. 7 shows the percentage energy savings in such cases. It is interesting to observe that AS is quite insensitive to the increase of the number of admissible antenna orientations. This behavior is explained by the fact that AS directs the antenna along the direction with the maximum traffic volume. For this reason, having more than two available orientations, does not affect the solution found for AS. On contrary, GP and WC are strongly sensitive to the number of available antenna orientations. As it can be observed, passing from 2 to 4 possible orientations, it results in an energy saving gap of about 20% and 45% for GP and WC, respectively. For instance, in the case of GP, the optimal orientation of the antennas is determined by assuming that the traffic volume between all the radio hub pairs is the same. Thus, for a generic antenna, a trade-off orientation is determined in such a way to satisfy all the directions.

5.3. Case study

As a real case study, we consider a complex heterogeneous platform shown in Fig. 8. The system is composed by a generic MultiMedia System which includes a H.263 video encoder, a H.263 video decoder, a MP3 audio encoder and a MP3 audio decoder [32], a MIMO-OFDM receiver [33], a Picture-In-Picture application (PiP) [34] and a Multi-Window Display application (MWD) [35]. Fig. 8 shows the application mapped on a HmWNoC [12] partitioned in 16 subnetworks where the upper level network is a 2D mesh topology augmented with three radio hubs. The number of

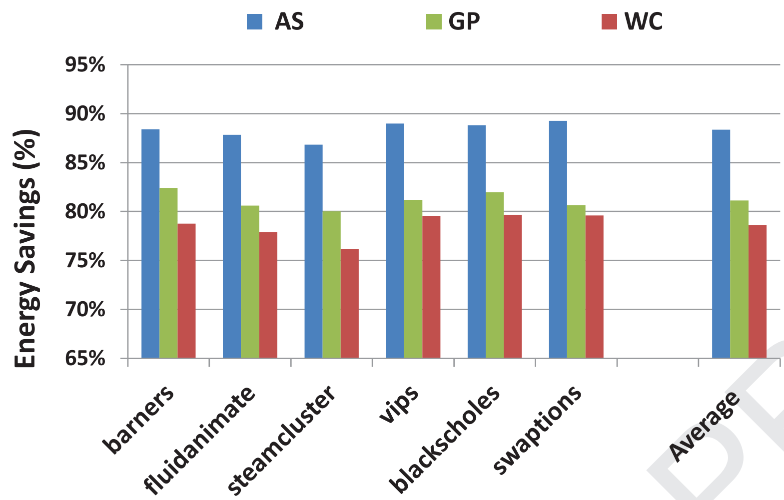

Fig. 5. Energy saving obtained for ms-WiNoC with 256 nodes under different traffic scenarios.

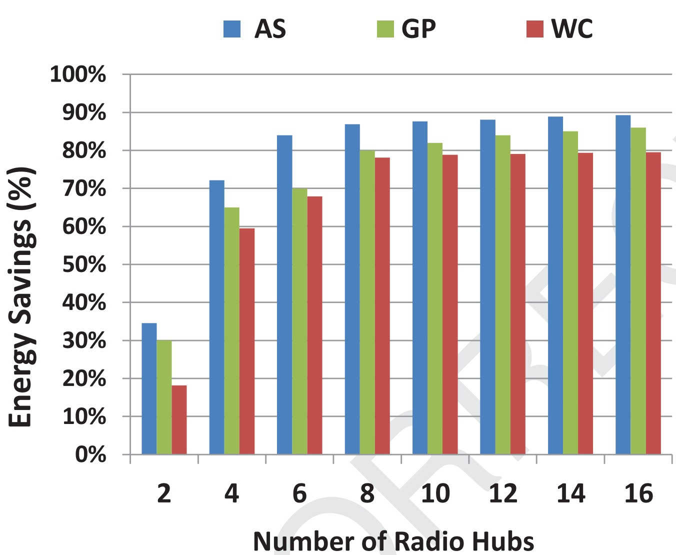

Fig. 6. Energy saving for different number of radio hubs.

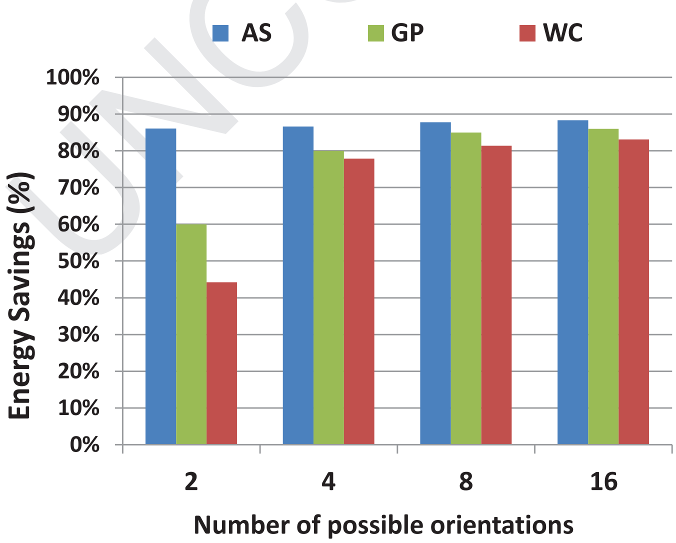

Fig. 7. Energy saving for various number of possible orientations of the antenna (WiNoC configured with 16 radio hubs).

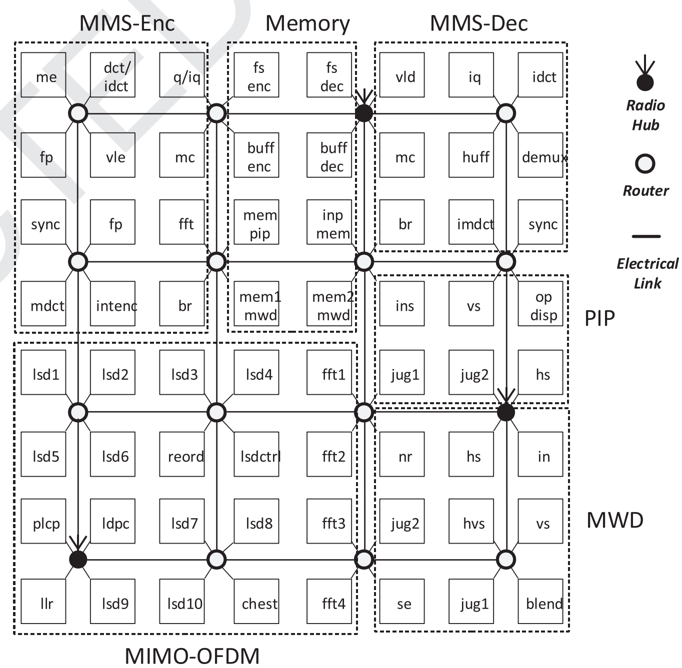

Fig. 8. Heterogeneous system composed by a multimedia sub-system, a MIMO-OFDM receiver, a PIP and a MWD module.

radio hubs and their placement into the network has been derived by using the optimization procedure described in [12].

We explore the antennas orientation design space for both the application specific (AS) and worst case (WC) scenarios. We consider antennas can be oriented among four angles (0°, 45°, 90°, 135°). We assume a tunable power amplifier supporting seven power steps with a transmitting energy per bit ranging from 0.42 pJ/bit to 1.4 pJ/bit. Fig. 9 shows the optimal orientation of the three antennas for the two scenarios. With regard to the AS scenario, due to the presence of memory elements close to C14, which represents an hot-spot region of the network, there is a relevant traffic volume between such region and both C0 and C7. Based on this, as can be observed from Fig. 9 (AS), both antennas in C7 and C0 are oriented in such a way to reduce energy when communicate with C14. With regard to the WC scenario, since no traffic information is used during the design space exploration, the optimal orientation of the antennas found, tries to minimize the

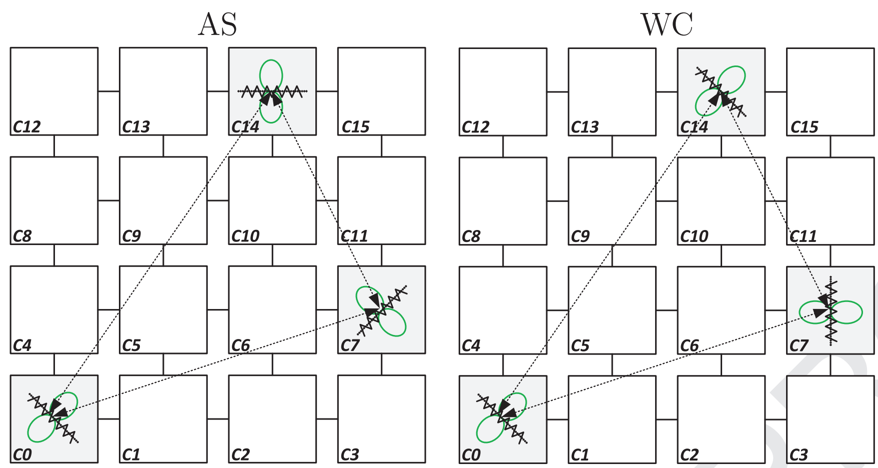

Fig. 9. Optimal antennas orientations found by the simulated annealing algorithm for the application specific (AS) and worst case (WC) scenarios.

Table 2
Transmitting energy per bit for each transmitting and receiving antennas pair.

		Transm. energy (pJ/bit)		
TX	RX	BS	AS	WC
C14	C7	1.40	0.58	1.07
C14	C0	1.40	1.23	1.07
C7	C14	1.40	0.58	1.07
C7	C0	1.40	0.91	1.07
C0	C14	1.40	1.23	1.07
C0	C7	1.40	0.91	1.07
Total energy (J)		1.68×10^{-4}	1.23×10^{-5}	1.02×10^{-4}

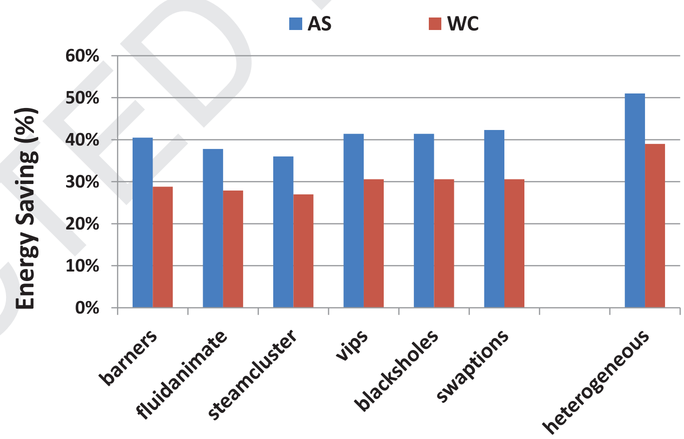

Fig. 10. Energy saving obtained for ms-WiNoC with 64 nodes under different traffic scenarios and for the heterogeneous platform of the case study.

worst case condition which is represented by the communication between the two far apart clusters, namely, C14 and C0. In fact, as it can be noticed, the antenna in C14 fits the directivity of the antenna in C0 and viceversa. This is due to the fact that, C0 is closer to C7 than C14. This scenario highlights, in fact, the importance of the distance *R* during the optimization process Eq. (9).

Table 2 reports, for each transmitting and receiving antennas pair, and for each considered scenario, the transmitting energy per bit. The table also shows a baseline scenario (BS) in which all the antennas have the same orientation (0°). Of course, for both the WC and BS scenarios, the transmitting energy is constant irrespective of the location of the transmitting and receiving antenna. The optimization of the antennas orientation in the WC scenario allows to reduce the communication energy by 39% as respect to the BS scenario. By considering the AS scenario, in which the transmitting power is tuned online, the communication energy reduces by 51%.

Please notice that, the energy saving figures obtained for the heterogeneous multimedia system, although they seem to be aligned with those found for the typical parallel applications (*i.e.*, SPLASH-2 and PARSEC), they are actually more relevant. In fact, the heterogeneous multimedia system is mapped on a 64-core NoC whereas the general parallel applications have been assessed on a 256-core NoC. For a more fair comparison, the same experiment, whose results have been shown in Fig. 5, has been repeated on a 64-node NoC and the obtained energy savings are shown in Fig. 10. As it can be observed, on average, the energy saving is 29% and 40% for the WC and AS scenarios, respectively, which is more than 10% less energy efficient of what has been observed for the heterogeneous case study. The higher energy saving obtained for the heterogeneous system is justified by the less uniformity of the communication patterns which characterizes heterogeneous systems and that are exploited by the proposed technique.

6. Conclusions

In a WiNoC the transceivers of the radio hubs account for a significant fraction of the total communication energy budget. Several work in literature in the context of low power WiNoC architectures, do not take into account the impact of the antenna directivity on power metrics. In addition, they assume that antennas present an omnidirectional radiation pattern which is far away from the reality (see, for instance, Fig. 4). In this paper we have highlighted the need for antennas orientation design space exploration for improving the energy figures of WiNoC architectures. We have considered three main scenarios, namely, application specific (AS), general purpose (GP), and worst case (WC). In the AS scenario, communication information are exploited for optimizing the orientation of the antennas in such a way to maximize the overlap of the radiation patterns of the antennas which communicate more. The GP scenario, is derived from AS by assuming that all the radio hubs communicate each other with the same probability. Finally, the WC scenario is when the transceiver does not implement any transmitting power on-line calibration scheme and, therefore, all the radio hubs communicate using the same transmitting power irrespective of their location in the chip. A state of the art small-world based WiNoC architecture has been used as reference WiNoC architecture in the experiments. The exploration of the antennas orientation design space under different traffic patterns resulted in important energy savings in all the three scenarios considered.

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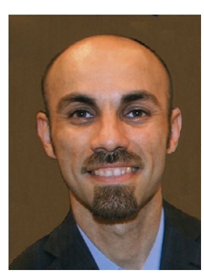

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