Simulation-based characterized environment for THz band Graphene antennas targeting WNoC

Ranjeet Singh
Advisor: Eduard Alarcón
Co-advisor: Albert Cabellos-Aparicio and Ignacio Llatser

Universitat Politècnica de Catalunya, Barcelona, Spain
Master of Science in Information and Communication Technology

2012
"The one who wants to learn to fly one day, must first learn to stand and walk and run and climb and dance, one cannot fly into flying."
Acknowledgements

I would like to dedicate a few lines to everyone who has made possible this thesis, to everyone who has supported me and contributed to make the stay in Universitat Politècnica de Catalunya. First of all, I would like to express my deep gratitude to Professors Eduard Alarcón and Albert Cabellos Aparicio for giving me the chance of coming to their lab, for their very valuable and always helpful advices and also for taking me in their big family. Without them, this thesis would not have been possible.

Secondly, I would like to sincerely thank Professor Josep Solé who advised me to join nano-group, as well as other faculties of UPC.

I would also like to thank all the members in the nano-group (Josep M. Jornet, Ignacio Llatser, Sergi Abadal Cavallé, Raúl Gómez Cid-Fuentes and Albert Mestres). Without you all, the way would have been longer and tougher and less exciting. Thank you for your feedback and support. I do not want to forget about the rest of the lab members, outstanding people, professional and charming. I have never met people like all of you. Thank you for making me feel part of a big family.

I would also like to appreciate everyone I met during my 2.5 years in UPC. Several classmates and friends. We have been sharing moments and helping each other every time we needed.

Last but not least, I would like to dedicate some words to my family. Thank you for the infinite support you have given to me and all the love I have gotten from you. Thank you a lot, everything I am, I owe to you.
Abstract

In a wireless Network-on-Chip system, two main factors are size of antennas and bandwidth. The Small size of antennas opens the possibility to integrate one antenna per core, where as their high bandwidth allows faster communication speed. Graphene based antennas offer perfect compromise of both small size and high bandwidth and for this reason, graphene is gaining importance in the field of wireless Network-on-Chip.

A wireless Network-on-Chip system based on graphene nano-antennas working in the THz range is analyzed in this thesis. In order to analyze WNoC systems, we consider a set of antennas deployed in an intra-chip scenario. In order to get meaningful results for antennas, simulations should be done in different environments. By getting the simulation results of antennas in free space and using them for comparison with results in a surrounded environment, we can get a better idea of the relationship between the size of these antennas and efficiency. A WNoC system based on graphene enabled antennas is described in this paper.

The main advantage of WNoC system is that we can inherit the properties of wireless communication. These properties are able to make the system more scalable as well as provide higher communication speed.

Keywords:
Terahertz, Graphene, Nano antennas, RF interconnects, 3D stacking, wireless network-on-chip.
## Contents

<table>
<thead>
<tr>
<th>List of Figures</th>
<th>iv</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Nanotechnology</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Brief history of graphene</td>
<td>2</td>
</tr>
<tr>
<td>1.3 The art of graphene drawing</td>
<td>3</td>
</tr>
<tr>
<td>1.4 Potential applications</td>
<td>4</td>
</tr>
<tr>
<td>2 Wireless networking on chip</td>
<td>6</td>
</tr>
<tr>
<td>2.1 Problem statement</td>
<td>6</td>
</tr>
<tr>
<td>2.2 Background on Network-on-Chip</td>
<td>6</td>
</tr>
<tr>
<td>2.2.1 CDLSI/CNT Interconnects</td>
<td>7</td>
</tr>
<tr>
<td>2.2.2 RF Interconnects</td>
<td>8</td>
</tr>
<tr>
<td>2.2.3 3D Stacking</td>
<td>8</td>
</tr>
<tr>
<td>2.2.4 Photonic NoC</td>
<td>10</td>
</tr>
<tr>
<td>2.3 Wireless Network on Chip</td>
<td>11</td>
</tr>
<tr>
<td>2.4 Research challenges in WNoC: motivation</td>
<td>12</td>
</tr>
<tr>
<td>2.5 Graphene-Wireless NoC</td>
<td>12</td>
</tr>
<tr>
<td>2.6 Graphene-based nano-antennas</td>
<td>14</td>
</tr>
<tr>
<td>3 Description of the simulation Framework</td>
<td>21</td>
</tr>
<tr>
<td>3.1 Brief description of FEKO</td>
<td>21</td>
</tr>
<tr>
<td>3.2 Definition of the scenarios</td>
<td>21</td>
</tr>
<tr>
<td>4 Simulation results</td>
<td>23</td>
</tr>
<tr>
<td>5 Conclusions and future work</td>
<td>29</td>
</tr>
<tr>
<td>Bibliography</td>
<td>30</td>
</tr>
</tbody>
</table>
List of Figures

1.1 Mother of all graphite forms. graphene is a 2D building material for carbon materials of all other dimensionality. It can be wrapped up into 0D buckyballs, rolled into 1D nanotubes or stacked into 3D graphite. ................................................................. 2

1.2 One-atom-thick single crystals: the thinnest material you will ever see. a, Graphene visualized by atomic-force microscopy (adapted from ref. 8). The folded region exhibiting a relative height of 4 clearly indicates that it is a single layer. b, A graphene sheet freely suspended on a micron-size metallic scaffold. Scanning-electron micro-graph of a relatively large graphene crystal, which shows that most of the crystals faces are zigzag and armchair edges as indicated by blue and red lines and illustrated in the inset. c, 1D transport along zigzag edges and edge-related magnetism are expected to attract significant attention ........................................ 5

2.1 Conceptual schematic of the multi-band RF-interconnect with six RF carriers. ................................................................. 9

2.2 Example of a 3D mesh. ............................................................. 10

2.3 Example of a multichannel transmission/reception scheme. Depending on the interconnection paradigm, the cores will communicate through a RF transmission line or an optical waveguide. Even though the principles are the same, frequency division multiplexing in photonics is oftentimes referred to as wavelength division multiplexing. ................................................................. 11

2.4 Example of a wireless vertical interconnect for 3D networks. The near field antennas can be of the capacitive or inductive type. ................................................................. 13

2.5 Dependence of the first resonance of a graphene patch nano antenna as a function of width. The absorption cross section normalized to the antenna width is shown. The antenna length is $L = 5 \mu m$. The plots correspond to infinite, $10\mu m$, $5\mu m$, $2\mu m$ and $1\mu m$ wide patches (right to left) ................................................................. 14
2.6 Absorption cross section of a graphene-based nano-patch antenna, for different substrate sizes: 6x6µm, 10x10µm, 16x16µm and infinite (below to above). .................................................. 17

2.7 Different positions of the graphene patch with respect to the substrate: patch in the center of the substrate (a), at 1.25µm from the center (b) and at 2.5µm from the center (c). ................................. 17

2.8 Absorption cross section of a graphene-based nano-patch antenna, for different positions of the graphene patch: in the center of the substrate (blue solid line), at 1.25 µm from the center (green dashed line) and at 2.5 µm from the center (red dotted line). ........ 18

2.9 Schematic diagram of the graphene-based nano-patch antenna in transmission. The antenna is composed of a graphene patch with a length $L = 5$ µm and a width $W = 1$ µm, and a pin feed located at 0.1 µm from the antenna edge. The blue circle shows the plane in which the radiation diagram is measured. .................. 19

2.10 Radiation pattern of a graphene (a) and metallic (b) nano-patch antenna as a function of its width. The plots show the normalized gain in dB, in the plane parallel to the antenna patch, for an antenna with a length $L = 5$ µm. The results correspond to antenna widths of $W = 1$ µm (blue solid line), 2 µm (green dashed line) and 5 µm (red dotted line). ......................... 20

3.1 Dependence of the first resonance of an infinitely wide Graphene based nano-patch antenna as a function of its length. The solid line is as calculated using the analytical model and the stars correspond to the resonance frequencies by simulations. ............... 22

4.1 3D view of nano patch antenna .................................................. 23

4.2 $S_{11}$ of nano patch antennas in free space ................................. 24

4.3 $S_{21}$ of nano patch antennas in free space ................................. 25

4.4 Current in transmitting nano patch antenna ................................. 26

4.5 Current in receiving nano patch antenna ................................... 26

4.6 $S_{11}$ of nano patch antennas covered by a hollow metallic box ....... 27

4.7 $S_{21}$ of nano patch antennas covered by a hollow metallic box ....... 27

4.8 Power loss due to impedance mismatch. ................................. 28
Chapter 1

Introduction

1.1 Nanotechnology

In this fast growing world we need everything fast and portable. Now human beings want a lot of applications in a small device, instead of separate device for each application. Nanotechnology is the way to achieve the challenges. Nanotechnology is able to create many new materials and devices with a vast range of applications, such as in medicine, electronics, bio-materials and energy production. Nanotechnology is very diverse, ranging from extensions of conventional device physics to completely new approaches based upon molecular self-assembly, from developing new materials with dimensions on the nano-scale to direct control of matter on the atomic scale. Nanotechnology spans fields of science as diverse as surface science, organic chemistry, molecular biology, semiconductor physics, micro-fabrication, etc. Graphene is one of the best example of nanotechnology as this material has many new characteristics which show great potential for future nano devices.

Graphene is a rapidly rising star on horizon materials science and condensed matter physics. It is a strictly two dimensional material exhibits exceptionally high crystal and electronic quality [1]. Graphene is a name given to a flat monolayer of carbon tightly packet in two dimensional (2D) honeycomb, and this is a basic building block for graphitic materials of all other dimensionality, Figure 1.1. It can be wrapped up into 0D fullerence, rolled into 1D nanotubes or stacked into 3D graphite. Theoretical graphene (or ”2D graphite”) has been studied for sixty five years and it is widely used for describing various carbon based materials. Graphene also provides an excellent condensed matter analogue of (2+1)-dimensional quantum electrodynamics, which propelled graphene into a thriving
Figure 1.1: Mother of all graphite forms. graphene is a 2D building material for carbon materials of all other dimensionality. It can be wrapped up into 0D buckyballs, rolled into 1D nanotubes or stacked into 3D graphite.

theoretical toy model [2], [3], [4].

### 1.2 Brief history of graphene

Before reviewing the earlier work on graphene, it is useful to define what 2D crystals are. Obviously, a single atomic plane is a 2D crystal, whereas 100 layers should be considered as a thin film of a 3D material. But how many layers are needed to make a 3D structure? For the case of graphene, the situation has recently become reasonably clear. It was shown that the electronic structure rapidly evolves with the number of layers, approaching the 3D limit of graphite already at 10 layers [5]. Moreover, only graphene and, to a good approximation, its bi-
layer have simple electronic spectra: they are both zero-gap semiconductors (can also be referred to as zero-overlap semi metals) with one type of electrons and one type of holes. For 3 and more layers, the spectra become increasingly complicated: Several charge carriers appear [6], [7] and the conduction and valence bands start notably overlapping [5], [6]. This allows one to distinguish between single-, double- and few- (3 to 10) layer graphene as three different types of 2D crystals (graphenes). Thicker structures should be considered, to all intents and purposes, as thin films of graphite. From the experimental point of view, such a definition is also sensible. The screening length in graphite is only 5 (that is, less than 2 layers in thickness) [7] and, hence, one must differentiate between the surface and the bulk even for films as thin as 5 layers [7], [8].

1.3 The art of graphene drawing

In the absence of quality graphene wafers, most experimental groups are currently using samples obtained by micro-mechanical cleavage of bulk graphite, the same technique that allowed the isolation of graphene for the first time [6], [10]. After fine-tuning, the technique [10] now provides high-quality graphene crystallites up to 100 m in size, which is sufficient for most research purposes (see Figure 2). Superficially, the technique looks as nothing more sophisticated than drawing by a piece of graphite [10] or its repeated peeling with adhesive tape [6] until the thinnest flakes are found. A similar approach was tried by other groups (earlier [9] and independently [11], [12]) but only graphite flakes 20 to 100 layers thick were found. The problem is that graphene crystallites left on a substrate are extremely rare and hidden in a haystack of thousands thick (graphite) flakes. So, even if one were deliberately searching for graphene by using modern techniques for studying atomically thin materials, it would be impossible to find those several micron-size crystallites dispersed over, typically, a 1-cm² area. For example, scanning-probe microscopy has too low throughput to search for graphene, whereas scanning electron microscopy is unsuitable because of the absence of clear signatures for the number of atomic layers.

The critical ingredient for success was the observation [6], [10] that graphene becomes visible in an optical microscope if placed on top of a Si wafer with a carefully chosen thickness of SiO2, owing to a feeble interference-like contrast with respect to an empty wafer. If not for this simple yet effective way to scan substrates in search of graphene crystallites, they would probably remain undiscovered today. Indeed, even knowing the exact recipe [6], [10], it requires special care and perseverance to find graphene. For example, only a 5 percentage difference in SiO2 thickness (315 nm instead of the current standard of 300 nm) can make single-layer graphene completely invisible. Careful selection of the initial
graphite material (so that it has largest possible grains) and the use of freshly -cleaved and -cleaned surfaces of graphite and SiO2 can also make all the difference.

Graphene’s quality clearly reveals itself in a pronounced ambipolar electric field effect such that charge carriers can be tuned continuously between electrons and holes in concentrations n as high as $10^{13} \text{cm}^{-2}$ and their mobilities can exceed 15,000 $\text{cm}^2/\text{Vs}$ even under ambient conditions [6], [11]. Moreover, the observed mobilities weakly depend on temperature T, which means that at 300K is still limited by impurity scattering and, therefore, can be improved significantly, perhaps, even up to 100,000 $\text{cm}^2/\text{Vs}$. Although some semiconductors exhibit room-temperature as high as 77,000 $\text{cm}^2/\text{Vs}$ (namely, InSb), those values are quoted for undoped bulk semiconductors. In graphene, remains high even at high n (> $10^{12} \text{cm}^{-2}$) in both electrically and chemically- doped devices [13], which translates into ballistic transport on sub-micron scale (up to 0.3 m at 300K). A further indication of the system’s extreme electronic quality is the quantum Hall effect (QHE) that can be observed in graphene even at room temperature, extending the previous temperature range for the QHE by a factor of 10.

1.4 Potential applications

1. Room temperature distillation of ethanol for fuel and human consumption: Graphene oxide membranes have been shown to be impermeable to all gases including helium, while simultaneously allowing water vapor to pass through the membrane as though no barrier were there [14].

2. Single molecule gas detection: Micrometre-size sensors made from graphene are capable of detecting individual events when a gas molecule attaches to or detaches from graphenes surface[13].

3. Graphene nano ribbons, transistors, optical modulators and integrated circuits.
Figure 1.2: One-atom-thick single crystals: the thinnest material you will ever see. 

a, Graphene visualized by atomic-force microscopy (adapted from ref. 8). The folded region exhibiting a relative height of 4 clearly indicates that it is a single layer. b, A graphene sheet freely suspended on a micron-size metallic scaffold. Scanning-electron micro-graph of a relatively large graphene crystal, which shows that most of the crystal’s faces are zigzag and armchair edges as indicated by blue and red lines and illustrated in the inset. c, 1D transport along zigzag edges and edge-related magnetism are expected to attract significant attention.
Chapter 2

Wireless networking on chip

2.1 Problem statement

As we are growing fast and we are using computer in almost all tasks so we need a computer which is more fast and powerful than we had 10 years ago. To increase the speed and performance of processors, a new term came in existence known as multi-core processor.

A multi-core processor is an integrated circuit (IC) to which two or more processors have been attached for enhanced performance, reduced power consumption, and more efficient simultaneous processing of multiple tasks [15]. The first multi-core processor was known as dual core as it had 2 cores. A dual core set-up is somewhat comparable to having multiple, separate processors installed in the same computer, but because the two processors are actually plugged into the same socket, the connection between them is faster. It was just starting of multi-core processor, and now we have processors with cores more than 2, like 8, 16. In near future we will have processors of 1000 cores.

2.2 Background on Network-on-Chip

As we are increasing the number of cores on a single chip, we need to connect them in order to get maximum performance. To achieve this, we are using many techniques which comes under the concept of Networking-on-Chip (NoC). NoC is a term which represents the way of communication between different cores. The on-chip communication network is becoming a critical component, affecting not only the performance and power consumption of multi-core processors, but also programming productivity [16]. Modern on-chip electrical interconnects (Els) are realized using copper wires. On-chip Els can be classified into two categories 1. Local interconnects: used for short distance communications, and have a delay
of less than a clock cycle.

2. Global interconnects: which are fewer in number, used for long distance communication and have a delay spanning multiple cycles. Long global Els typically have high RC constants, which results in greater propagation delay, transition time and crosstalk noise. As a consequence in on-chip communications it is becoming increasingly harder for a copper-based electrical interconnects to satisfy design requirements like delay, power, bandwidth, delay uncertainty [17].

The steep rise in parasitic resistance and capacitance of copper interconnects poses serious challenges for interconnect delay, specially at the global interconnects. Copper interconnects also constitute up to the 70 percentage of total on-chip capacitance, major sources of power dissipation [17].

Therefore we need some new technologies which can replace the copper interconnects in order to satisfy performance, reliability, power requirements in long term, support ultra high data rates and be scalable enough to support tens to hundreds of concurrent communication streams.

So far people proposed following solutions: CDLSI/CNT Interconnects, RF/Wireless Interconnects, 3D Stacking and Optical Interconnects. These solutions are detailed next.

2.2.1 CDLSI/CNT Interconnects

A paradigm shift toward high performance multi-core processors requires global wires with low latency, low power, and high bandwidth density. Conventional Cu/low-k technology presents a serious performance barrier. While these interconnect schemes exhibit promise for meeting future system wire requirements, they suffer from serious technological/practical challenges. On the other hand, a new low swing interconnect circuit scheme - ‘capacitively driven low swing interconnects’ (CDLSI) is highly practical, while being equally promising.

Conventional low swing interconnects (where logic operations are done at normal voltages, however, signal transmission is done at a reduced voltage) are attractive as they tackle the wire energy problem head-on by reducing dynamic power. However, this advantage is typically accompanied by a latency penalty and a reduction in the noise margin. Moreover, they usually require a secondary low voltage power supply, which makes the system more expensive and complex. Recently, CDLSI was shown to exhibit excellent energy saving without seriously impacting latency [21], [22], [23]. Key element in this system is the coupling capacitance, which not only eliminates the necessity of a secondary power supply, but also introduces pre-emphasis, resulting in bandwidth improvement. Wires are differential and twisted in order to cancel the coupling noise.

The idea is to find the interconnect, which can do the job fastest and with
least power. CDLSI shows clear delay advantage below 10Gbps bandwidth range due to its pre-emphasis effect. However, the maximum allowed bandwidth for CDLSI is much less than the conventional wire due to the performance limits of transmitter/receiver. CNTs can further reduce delay for both circuit schemes with their advantage over Cu by improving PD(packing densities) and MFP(mean free path) (PD=1, MFP=2.3µm) [23]. However, it still remains unclear whether the mere replacement of interconnect materials will be sufficient to extent the lifetime of conventional on-chip networks beyond a few technology generations.

2.2.2 RF Interconnects

To reduce delay and improve performance with high bandwidth, researchers started looking for scalable alternatives in the physical layer design. As an alternative, RF Interconnects (RF-I) came in light. Compared with CMOS repeaters charging and discharging the wire, EM waves travel in a guided medium at the speed of light, so the propagation delay is reduced significantly and becomes independent of link length. RF-interconnects can achieve high speed, seamless re-configurability, and simultaneous communications between multiple I/O users via multiple frequency bands by using shared physical transmission lines. We can increase the data rate by using multi-band RF-I based on frequency-division-multiple-access algorithms (FDMA) or by using code-multiplexed signals through a shared transmission line (see figure 2.1) [24], [25].

As RF-I supports Multicast, so it allows the interconnection of multiple core using the same transmission line by assigning each core a channel and thus reducing the number of on chip wires. Other important thing both RF/wireless interconnect system and components can be implemented based on a silicon-based CMOS technology, which is and will continue to be the mainstream of the future ULSI industry.

Even though RF-I improve the performance but they also have some open challenges. Implementation of I/O transceivers produces circuitry overhead and power consumption, FDMA-interconnect requires high quality bandpass filters for high spectrum efficiency. Since the reference crystal oscillator needed for FDMA cannot be easily implemented on-chip and its size is relatively large compared with future ULSI, it appears as an issue [26].

2.2.3 3D Stacking

The other option in CMOS processes is 3-dimensional (3D) stacking [27], in which several layers of active devices are superposed to achieve a higher level of integration. Due to vertical integration, the same functionality can be implemented in a smaller chip area, reducing both cost and the distance signals required
Figure 2.1: Conceptual schematic of the multi-band RF-interconnect with six RF carriers.

Reduced distance decreases both transmission latency and the consumed energy. 3D-stacking also shows improved noise immunity and overall superior performance [28].

3D-stacking has its own advantages. For instance it reduces the length of local and global wires. It also allows to use of topologies not considered in the 2D design space, potentially yielding better multi-hop latency results [29]. It also allows to use of different technologies in hybrid approaches.

However, 3D stacking requires vertical connection between transistor and metal tiers, usually implemented using metal studs that cut through layers of silicon and insulators. Alignment of such direct connection is difficult on a large scale and therefore requires a relatively large connection area. Along with this, superposition of active layers produces an increase in the heat density that must be circumvented in order to avoid thermal effects.
2.2.4 Photonic NoC

Recent advances in silicon photonics are enabling the integration of optical systems over silicon layers with existing CMOS chip manufacturing techniques. Consequently, silicon photonics have paved the way for the creation of optical intra-chip interconnection networks or photonic NoCs. Signals are converted from the electrical to the optical domain, modulated and sent through a switched network of optical wave-guides until reaching the receiver, where the signal is converted back to the electrical domain.

The photonic NoC paradigm provides low delay and huge bandwidths for data transmission, as well as highly improved power consumption figures. Two particular properties of optical communications related with power consumption (i.e. bit-rate transparency and low loss in optical wave-guides) explain such advantages [30]. On the one hand, bitrate transparency refers to the fact that the dynamic power consumption does not depend on the transmission bit-rate, since optical switches only change its state once per message. This allows the transmission of high-bandwidth messages in a highly energy efficient manner. On the other hand, low loss in optical wave-guides causes the power dissipated in photonic links to be nearly independent of the transmission distance [30].

However, implementing all-optical basic functions such as buffering or header processing for routing is a highly challenging task. Without these functions, the creation of a photonic on-chip packet-switched network would require an enormous amount of optoelectronic converters thus rendering this approach infeasible.

Figure 2.2: Example of a 3D mesh.
Figure 2.3: Example of a multichannel transmission/reception scheme. Depending on the interconnection paradigm, the cores will communicate through a RF transmission line or an optical wave-guide. Even though the principles are the same, frequency division multiplexing in photonics is often-times referred to as wavelength division multiplexing.

ble. Conversely, the implementation of a parallel electric NoC control channel has been proposed [30]. The resulting hybrid NoCs would be composed of a packet-switched electric control plane and a circuit-switched optical data plane, which offers a high bandwidth density by means of Wavelength Division Multiplexing (WDM). For instance, Figure 2.3 shows how two cores communicate through an optical waveguide using three different channels, of wavelengths $\lambda_1$, $\lambda_2$ and $\lambda_3$ [31].

The physical implementation of on-chip photonic networks is hampered by the immaturity of the underlying technologies. Considerable research efforts are being devoted to the development of efficient and high-bandwidth silicon modulators, switching elements and photo-detectors, as well as of integrated on-chip light sources.

2.3 Wireless Network on Chip

With the new developed EM field solver simulators (like FEKO) and CMOS integration, allows developers to design and implement on-chip antennas. As with the technology downscaling now we have RC circuits working on multi GHz band.
Such high frequencies gives a hint that on chip metallic antennas will have a size in the range of hundreds of micrometers.

However we are talking about wireless network on chip, but complete wireless network on chip is not existing yet. Hence here WNoC refers to the hybrid approach, where we have traditionally wired links and wireless links. If we can create a complete wireless network on chip it will allow network architecture to take advantages of the unique features of wireless communication.

There are several advantages of wireless communications basically inheriting form RF interconnect, like broadcast/multicast as signals are transmitted in air and can be received by any receiver in the transmission range. Low latency as the signals are transmitted in air at nearly speed of light also wireless transmission reduces the multi-hop latency. Scalability effect can be reduced a lot using wireless communication as we get excellent results in terms of latency and energy consumption [32]. And reconfigurability is also feasible in communication without changing in physical structure.

2.4 Research challenges in WNoC: motivation

When we talk about WNoC, it sounds like a fast processor with high possibilities to increase the number of cores. But still we don’t have a communication protocols for wireless networking on chip and on top of that the size of future metallic antennas i.e. hundreds of micrometers [33] seems to be infeasible to put an antenna per core as size of cores continue to shrink with each CMOS technology generation and they reach sizes of micrometers. We know that bandwidth is generally inversely proportional to the antenna size and metallic antennas do not look like a good option in high data intensive environment. This issues can not be solved by just reducing the size of metallic antennas because such small size imposes the use of very high frequencies near to optical range, which present several drawbacks. Such as their high attenuation and the difficulty of implementing optical circuits.

2.5 Graphene-Wireless NoC

As we can not follow metallic antennas for future WNoC, we take graphene as an alternative to create nano antennas. Graphene-based nano-antennas just a few micrometers in size, i.e. two orders of magnitude below the dimensions of equivalent metallic on-chip antennas, could provide inter core communication in the terahertz (0.1-10 THz) band. These characteristics will both enable size compatibility with each processor core and offer compatibility with each processor core.
and offer enough bandwidth in massively parallel multiprocessor [34].

We have talked about graphene in introduction part and one existing property surface plasmon polariton effects causes the wave propagation velocity inside this material to be significantly lower than in other metallic materials [19], [35]. Since the radiation frequency is determined by the dimensions of the antenna and the wave propagation velocity inside the antenna material, graphene antennas will be significantly smaller than their metallic counterparts for the same radiation frequency. So graphene gives us possibility to create small size antennas with high frequency, so we are able to put one antenna on each core. Figure 2.4 shows a simple conceptual implementation of a Graphene-Wireless-NoC, where all the processor cores are equipped with a graphene-based nano antenna and a nano-transceiver. Figure 2.5 shows the resonance behaviour of a graphene based nano-

![Graphene-Wireless-NoC diagram](image)

**Figure 2.4**: Example of a wireless vertical interconnect for 3D networks. The near field antennas can be of the capacitive or inductive type.

patch antenna of length $L = 5\mu m$ as a function of width $(W)$, calculated by means of numerical simulation. These and other results shown in [35], suggest that the
antenna operating frequency can be tuned over the THz band by adjusting the antenna width and length. My aim to do this thesis is to find coupling between different graphene based antennas.

Figure 2.5: Dependence of the first resonance of a graphene patch nano antenna as a function of width. The absorption cross section normalized to the antenna width is shown. The antenna length is \( L = 5 \, \mu \text{m} \). The plots correspond to infinite, \( 10 \, \mu \text{m} \), \( 5 \, \mu \text{m} \), \( 2 \, \mu \text{m} \) and \( 1 \, \mu \text{m} \) wide patches (right to left).

I used a simulation tool known as FEKO to perform my analysis, and in next chapter you’ll find complete description of simulation framework.

2.6 Graphene-based nano-antennas

In previous year some fundamental work has been done on graphene based Nano-antennas. I would like to put some light on this work in order to make the scenario more clear and to explain state-of-the-art of graphene based Nano-antennas. I’ll
follow a paper "Characterization of Graphene-based Nano-antennas in the Terahertz Band" which is published recently[37].

Graphene presents excellent conditions for the propagation of Surface Plasmon Polaritons (SPP), waves guided along a metal-dielectric interface which are generated by an incident high-frequency radiation. Indeed, a free-standing graphene layer supports transverse-magnetic (TM) SPP waves with an effective mode index given by [36]

$$n_{\text{eff}}(\omega) = \sqrt{1 - 4 \mu_0 \frac{1}{\varepsilon_0 \sigma(\omega)^2}}.$$ \hspace{1cm} (2.1)

While SPP modes are not supported by free space, in a graphene-based nano-patch antenna, the edge of the graphene patch acts as a mirror and the patch behaves as a resonator for SPP modes. The coupling of the incident electromagnetic radiation with the corresponding SPP modes leads to resonances in the graphene-based nano-patch antenna. The resonance condition is given by

$$m \frac{1}{2} \frac{\lambda}{n_{\text{eff}}} = L + 2\delta L,$$ \hspace{1cm} (2.2)

where $m$ is an integer determining the order of the resonance, $\lambda$ is the wavelength of the incident radiation, $L$ is the antenna length and $\delta L$ is a measure of the field penetration outside the graphene-based nano-patch antenna. This equation determines a set of $m$ resonance frequencies $\omega_m$ corresponding to $m$ modes of the resonator.

We consider graphene-based nano-patch antennas with a size of a few micrometers, small enough so that they can be integrated into a nano-system. Since the effective mode index $n_{\text{eff}}$ in graphene is in the order of $10^2$ [36], according to this model, the first resonance frequency of our envisaged graphene-based nano-patch antennas lies in the terahertz band, around two orders of magnitude below what it would be expected in a perfect metallic antenna. This is one of the main reasons why graphene-based nano-antennas are seen as the enabling technology for wireless communications at the nano-scale. Next, this prediction will be validated and the performance of these antennas will be further explored by means of simulation.

As a first approximation, in previous work [35] modelled antenna was a graphene patch suspended in air. Figure 3.1 shows the position of the first resonance of a such an antenna as a function of its length. The analytical expression, as obtained from this model, is compared with the results of numerical simulations done using the method of moments with surface equivalence principle [18]. The antenna is modelled as an infinitely wide graphene patch with length $L=5\mu$m, and a plane wave normally incident to the antenna is considered. The penetration length is
set to $\delta L = 0.5 \mu m$. As it can be observed, the simulation results show a very good agreement with the analytical model.

A realistic graphene-based nano-patch antenna, however, will have a finite width. Figure 2.5 shows the absorption cross section of a $5 \mu m$-long graphene-based nano-patch antenna as a function of its width, calculated by numerical simulation. The absorption cross section is a measure of the fraction of the power of the incident wave that is absorbed by the antenna; therefore, the antenna resonant frequency coincides with the frequency at which the absorption cross section is maximum. We can see in Figure 2.5 that the antenna resonant frequency is reduced as the antenna becomes narrower. These results suggest that, by adjusting the antenna dimensions, its operation frequency can be tuned in a wide spectral range.

It is worth investigating the behaviour of a graphene-based nano-patch antenna when a more realistic model is used. We consider next an antenna modelled as a graphene patch deposited on a dielectric substrate. We analyze the dependence of the antenna absorption cross section on the substrate size, when a plane wave is normally incident to the antenna. We consider an antenna made of a graphene patch with a size of $5 \times 0.5 \mu m$ located on the center of a silicon substrate with a square shape and a thickness of $1 \mu m$. Figure 2.6 shows the absorption cross section of this graphene-based nano-patch antenna for different substrate sizes, from $6 \times 6 \mu m$ to infinity. On the one hand, it can be seen that a larger substrate improves the antenna performance, since the absorption cross section increases with the substrate size, up to a certain limit. On the other hand, the antenna resonant frequency is shown to be virtually constant at $0.5$ THz, independently of the substrate size[37].

Next, we evaluate the influence of the patch position relative to the substrate in a graphene-based nano-patch antenna. The considered substrate has dimensions of $6 \times 6 \mu m$ and a thickness of $1 \mu m$. The graphene patch measures $5 \times 0.5 \mu m$ and is located in three different positions, as shown in Fig. 2.7: in the center of the substrate (2.7a), at $1.25 \mu m$ from the center (2.7b) and at $2.5 \mu m$ from the center (2.7c). Fig. 2.8 shows the antenna absorption cross section as a function of frequency, for each of these three configurations. As it can be observed, the absorption cross section increases as the graphene patch is located closer to the side of the substrate. Moreover, the resonant frequency becomes higher when the patch is farther from the center. These results indicate that, for a given substrate size, the optimal location for on-chip graphene-based nano-antennas may be near the edge of the substrate, in order to maximize their efficiency.

Finally, it is also interesting to study the properties of graphene-based nano-patch antennas in transmission. With this purpose, a terahertz signal is driven into the antenna, modelled as a free standing graphene patch by means of a pin feed. A simulation study of a transmitting graphene-based nano-patch antenna is
Figure 2.6: Absorption cross section of a graphene-based nano-patch antenna, for different substrate sizes: 6x6µm, 10x10µm, 16x16µm and infinite (below to above).

Figure 2.7: Different positions of the graphene patch with respect to the substrate: patch in the center of the substrate (a), at 1.25µm from the center (b) and at 2.5µm from the center (c).
Figure 2.8: Absorption cross section of a graphene-based nano-patch antenna, for different positions of the graphene patch: in the center of the substrate (blue solid line), at 1.25 µm from the center (green dashed line) and at 2.5 µm from the center (red dotted line).
Figure 2.9: Schematic diagram of the graphene-based nano-patch antenna in transmission. The antenna is composed of a graphene patch with a length $L = 5 \mu m$ and a width $W = 1 \mu m$, and a pin feed located at $0.1 \mu m$ from the antenna edge. The blue circle shows the plane in which the radiation diagram is measured.

performed, which allows obtaining its radiation pattern. The antenna has a fixed length $L = 5 \mu m$, while its width takes the values $W = 1, 2$ and $5 \mu m$ (the geometry for the case $W = 1 \mu m$ is shown in Fig. 2.9). The pin feed is located at a distance of $0.1 \mu m$ from the antenna edge. Fig. 2.10a shows the radiation pattern of graphene-based nano-patch antennas with the described properties, in the plane parallel to the graphene patch.

Fig. 2.10b shows the radiation pattern of equivalent metallic antennas, modeled as perfect electric conductor patches of the same dimensions. The radiation pattern is computed at a frequency of $1.3 \text{THz}$, which approximately corresponds to the resonant frequency of a graphene-based nano-patch antenna of the previous dimensions. Even though the metallic antenna is expected to resonate at a higher frequency band, the analysis is performed at the same frequency for the sake of comparison. As it can be seen, in both cases the radiation pattern is similar to that of a half-wave dipole antenna, and the differences between the patterns of graphene and the metallic antennas are minimal. We therefore conclude that, as it could be expected, the radiation pattern of future graphene-based nano-patch antennas will not differ significantly with respect to that of equivalent metallic antennas.
Figure 2.10: Radiation pattern of a graphene (a) and metallic (b) nano-patch antenna as a function of its width. The plots show the normalized gain in dB, in the plane parallel to the antenna patch, for an antenna with a length $L = 5 \mu m$. The results correspond to antenna widths of $W = 1 \mu m$ (blue solid line), $2 \mu m$ (green dashed line) and $5 \mu m$ (red dotted line).
Chapter 3

Description of the simulation Framework

3.1 Brief description of FEKO

FEKO is a general purpose software product developed by EM Software and Systems - S.A. (Pty) Ltd for the simulation of electromagnetic fields. This software is based on Method of Moments (MoM) integral formulation of Maxwell equations and pioneered the commercial implementation of various hybrid methods.

The Method of Moments (MoM) is a full wave solution of Maxwell’s integral equations in the frequency domain. An advantage of the MoM is that it is a ”source method” meaning that only the structure in question is discretized, not free space as with field methods. Boundary conditions do not have to be set and memory requirements scale proportional to the geometry and the required solution frequency [18].

There are several simulation software’s are available but most of them support simulation in a same plane but FEKO is a good software to perform simulations in different planes. Although my work is just in single plane but as we will need this feature in future in 3D design, so it’s a good way to start work with a future strategy.

3.2 Definition of the scenarios

In this section I’ll give you explanation about my model in FEKO. Basically I tried to find out the coupling between two antennas in free space and in surrounded area. Size of the antennas is a big issue in this work as we are working to increase the capacity and to reduce interconnects area.
In my work I kept the antennas size in micrometers [19], [20] as my motive is to work in frequency range between 0.1 THz to 10 THz. The resonance length of graphene antennas has been defined previously [20] in figure 3.1. In my model I used one infinite long multi layers substrate with 50 micrometer thickness and the graphene patches were separated by 30 micrometers (center to center). The dimensions of graphene patch are 12 micrometers long and 2 micrometers wide. I used wire ports to feed the antennas in order to calculate the currents in the ports, which can give an idea about how much current we are using in transmitting antenna and how much current we are receiving in receiver antenna( figure 4.4 and figure 4.5).

First I made some single antennas to calculate the S11, by changing the thickness of substrate and dimensions of graphene patch in the end I found very good results of S11. I kept those dimensions for my work as mentioned above.

Figure 3.1: Dependence of the first resonance of an infinitely wide Graphene based nano-patch antenna as a function of its length. The solid line is as calculated using the analytical model and the stars correspond to the resonance frequencies by simulations.
Chapter 4

Simulation results

Figure 4.1 shows the 3D view of antenna, which has a wire port for power feeding. We used the infinite long substrate and put the patch antennas 30 micrometers far (center to center). First we calculated S11 and S12 of antennas in free space and then surrounded by a hollow metallic box of 200 micrometer height.

Figure 4.1: 3D view of nano patch antenna

Figure 4.2 shows the S11 in free space and figure 4.3 shows S21 in free space. In general case of antennas we consider S11= -10db as a satisfactory result. In figure 4.2 we can see that, in free space we got S11= -9.2 db which is very close to general expectations. Second thing we can notice in figure 4.2 is minimum S11
matches the resonance frequency and we received at 0.8 THz, which also supports the previous research on graphene as shown in figure 2.5 and figure 3.1. S11 is equivalent to the reflection coefficient and a good value of S11 shows that there is less reflection but it doesn’t say about radiation. So to proof there is radiation and reception in antennas, I’m also providing figures for currents in transmitter and receiver antennas (figure 4.4 and figure 4.5). In figures 4.4 and 4.5, Y-axis denotes the value of current in milliamperes and X-axis denotes the value of frequency in THz.

Length of antennas effects the resonance frequency and if we see the results shown in figure 2.5, resonance frequency for 10µm long antenna is 1THz. So getting a resonance frequency of 0.8THz for 12µm long antennas (figure 4.2) shows that measurement has done in good manner.

So if we see the figure 4.4 we will find that transmitting current is maximum at the same resonance frequency shown in figure 4.2. The maximum current is 118mA at a input power of 1 Watt. At the same movement we should observe receiving current graph. So in figure 4.5 we see that there is a peak at 0.8THz frequency, which is resonance frequency.

Figures 4.6 and 4.7 show S11 and S21 of antennas covered by a hollow metallic box. In figures 4.2, 4.3, 4.6 and 4.7, y-axis denotes the value of S-parameters in dB and X-axis denotes the value of frequency in THz. Figure 4.8 shows the power loss due to mismatch where Y-axis denotes the value of power loss in dB watt and X-axis denotes the value of frequency in THz. When we tried to calculate the S11 for same antenna in a hollow metallic box results were different. The resonance frequency shifted to 0.5THz, which is good because lower frequency

Figure 4.2: S11 of nano patch antennas in free space
get less distortion from environment. But we got poor value for S11(-5.8 dB). I predict the reason behind this is environment. As metallic box is conductive and can absorb radiated field. So if we replace the metallic box by plastic box, we will get better results.

Figure 4.3: S21 of nano patch antennas in free space
Figure 4.4: Current in transmitting nano patch antenna

Figure 4.5: Current in receiving nano patch antenna
Figure 4.6: S11 of nano patch antennas covered by a hollow metallic box

Figure 4.7: S21 of nano patch antennas covered by a hollow metallic box
Figure 4.8: Power loss due to impedance mismatch.
Chapter 5

Conclusions and future work

In my thesis I talked about wireless network on chip, and this topic is getting mature. But still we have not worked enough in the direction of fully wireless network on chip. So I tried to make some field-solver simulation-based characterization to check the potential of this approach. Resultant values of S11 in free space (figure 4.2) lies on 0.8 THz frequency with a value of -9.2db and S11 of antenna in hollow metallic box (figure 4.6) resonance frequency switches to 0.5 THz which is even better for communication. So these results are good enough to give a motivation for future research. These results follow the previous research by [19], [20], [35]. The main contribution here is that graphene antennas are characterized in a realistic WNoC scenario.

So far we don’t have clear values for graphene’s radiation capacity and we need to work on it. If we get some specific values for graphene radiation, picture for graphene antennas will be more clear. However if we look at the receiving current graph (figure 4.4), it is more or less following the transmitting current’s graph (figure 4.5). Which proves that graphene is radiating and resultant received current is caused by transmitting current. As transmitting antenna is radiating in all directions so receiving a low current in receiving antenna is normal.

For future work we can try to change the distance between antennas to explore near-field limits, cover them by plastic box and changing the dimensions of antennas and box as well. I believe that replacing metallic box by plastic box, will improve the results.
Bibliography


[14] Nair; Wu; Jayaram; Grigorieva; Geim (2012). "Unimpeded permeation of water through helium-leak-tight graphene-based membranes". Science 335 (6067): 4424


