Graphene-enabled Wireless Networks-on-Chip

(Invited Paper)

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***Abstract*—Graphene-enabled Wireless Communications (GWC) advocate for the use of graphene-based plasmonic antennas, or graphennas, which take advantage of the plasmonic properties of graphene to radiate electromagnetic waves in the terahertz band (0.1 – 10 THz). GWC may represent a breakthrough in the research areas of wireless on-chip communications, i.e., among the different processors or cores of a chip multiprocessor, and of these cores with the memory system. The main advantages of the resulting Graphene-enabled Wireless Networks on-Chip (GWNoC) are twofold. On the one hand, the potential of GWC to radiate in the terahertz band provides a huge transmission bandwidth, allowing not only the transmission of information at extremely high speeds but also the design of ultra-low-power and low-complexity schemes. On the other hand, the size of graphennas can be greatly reduced with respect to metallic antennas with the same resonant frequency, allowing the integration of graphennas within individual processing cores and the implementation of core-level wireless communication. In addition to these physical layer advantages, GWNoC represent a clear opportunity from the multicore architecture perspective. Due to their native implementation of broadcast and multicast communications, GWNoC will enable not just the alleviation of the latency or power bottlenecks of traditional on-chip networks, but also the devising of novel multicore architectures.**

I. INTRODUCTION

Graphene, a flat monoatomic layer of carbon atoms tightly packed in a two-dimensional honeycomb lattice, has recently attracted the attention of the research community due to its novel mechanical, thermal, chemical, electronic and optical properties [1], [2]. Since its first isolation by the Nobel laureates Andre Geim and Konstantin Novoselov back in 2004, graphene has given rise to a plethora of potential applications in fields ranging from ultra high-speed transistors, flexible displays to transparent solar cells, attracting, as a result, multimillion dollar research funding. Asian, American and European funding agencies have been increasing the incentives for the investigation of such promising material, leading to the award of a FET Flagship project, associated to a one-billion-euro grant, to the development of graphene devices and systems [3].

A remarkably promising application of graphene is that of Graphene-enabled Wireless Communications (GWC). GWC advocate for the use of graphene-based plasmonic nano-antennas, or *graphennas*, whose plasmonic effects allow them to radiate EM waves in the terahertz band (0.1 – 10 THz) [4], [5], the majority of which remains unregulated. Moreover, preliminary results sustain that this frequency band is up to two orders of magnitude below the optical frequencies at which metallic antennas of the same size resonate, thereby enhancing the transmission range of graphene-based antennas and lowering the requirements on the corresponding transceivers. In short, graphene enables the implementation of nano-antennas just a few micrometers in size that are not doable with traditional metallic materials.

Thanks to both the reduced size and unique radiation capabilities of graphennas, GWC may represent a breakthrough in the research area of both off-chip and on-chip communications. Off-chip communications concern the exchange of information between different chips of a given set. In this scenario, the typical transmission ranges are from 1 to 10 mm and the objective is to be able to transmit information at high data rates, around 1 Tbps. Some of the current bottlenecks in off-chip communications are the power consumption, the maximum data rate and the latency of current interconnection networks. The use of graphennas will solve these drawbacks while simplifying at the same time the physical device, by avoiding the physical interconnections. In most cases, the communication will be point to point, between two components in a chip.

A further step after off-chip communications considers applying the same concept to communicate different computing cores within a chip multiprocessor. Communications encapsulated in a single chip present some new advantages, such as the inherent broadcast nature of wireless interconnections, which allows to simplify broadcast communications. The typical transmission ranges in this case are from 100 μm to 5 mm, depending on the chip size and the density of nodes to connect in the chip.

The advantages of the application of GWC to off- and on-chip wireless communication are manifold, but they can be summarized in two key aspects. On the one hand, the potential of GWC to radiate in the terahertz band provides a huge transmission bandwidth, allowing not only the transmission of information at extremely high speeds but also the design of ultra-low-power and low-complexity schemes. On the other hand, the reduced size of such antennas results in a smaller area overhead than with conventional metallic antennas, factor that may be critical in area constrained scenarios. Moreover, improving the directivity values by means of graphene-based antenna arrays could be possible due to the aforementioned reduced size. This could help diminish the internal interference level, lowering the complexity of the Medium Access Control (MAC) protocols.

Two of the main research challenges which need to be investigated in order to apply GWC to off-chip wireless communications are the following: 1) to develop a complete terahertz channel model for off-chip Graphene-based Wireless Communications, and 2) to inspect the modulation/codification

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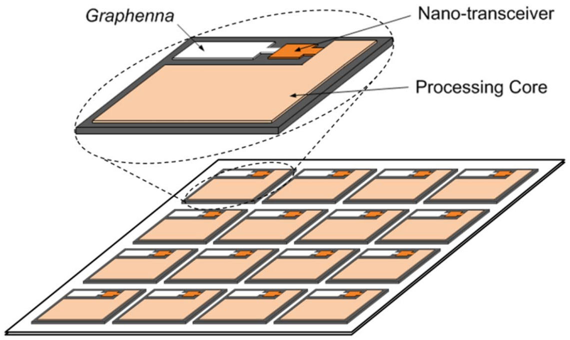

Fig. 1. Schematic representation of a 16-core Graphene-enabled Wireless Network-on-Chip (GWNoC).

design space. The terahertz channel can be modeled by means of Finite Element Method (FEM) simulations which take into account the two main peculiarities of the scenario: within-set and terahertz communication. The former affects aspects such as the static multipath effects due to the reflection of the EM waves on the different metallic surfaces, while the latter affects important parameters such as the path loss or the ambient noise and, therefore, the communication range and the channel capacity. Investigation on modulations needs to focus on the design of simple, efficient and high data rate modulations. The results given by the channel model shall be taken into account to determine the need for multipath- or collision-resistant schemes.

The integration of GWC in an on-chip scenario represents the logical continuation on their application in off-chip wireless communications. Indeed, the reduced size of graphennas (in the order of a few micrometers) enables their size compatibility with cores of current and future multiprocessors. In this context, graphennas can be also effectively used as a way to communicate the different processors or cores of a Chip Multiprocessor. This new communication technique is known as Graphene-enabled Wireless Network-on-Chip (GWNoC, illustrated in Fig. 1) [6]. Deployed over a state-of-the-art on-chip interconnection network [7], a GWNoC enables point-to-point, broadcast and multicast communications in the terahertz band, which potentially offers enough bandwidth in this data intensive scenario. From the multicore architecture perspective, such feature creates a large range of possibilities with potential to cause a paradigm shift in how processors interact between them and with memory [6], for instance in terms of data/cache coherence, consistency or synchronization. Some of the main research challenges in this area include the development of new communication protocols suited to GWNoC, as well as novel scalable multicore architectures that minimize many of the issues present in multiprocessor environments.

The remainder of this paper is organized as follows. Section II describes the main research challenges in the application of GWC to off-chip and on-chip wireless communications, and outlines some possible solutions. In Section III, some preliminary results in this research area are shown. Section IV gives a long-term vision on the field of GWNoC and its potential impact. Finally, Section V concludes the paper.

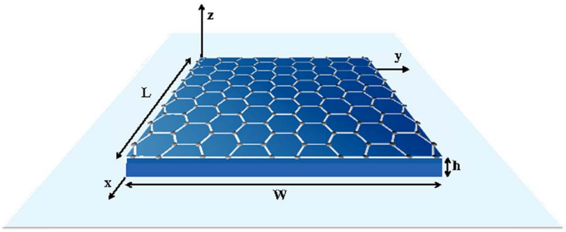

Fig. 2. Schematic diagram of a graphene-based plasmonic nano-patch antenna (graphenna).

II. RESEARCH CHALLENGES

Graphene-based plasmonic nano-antennas, or shortly named graphennas, are the cornerstone of GWC. A graphenna is composed of a finite-size graphene patch with a length and width between 1 and 10 micrometers mounted over a metallic flat surface (the ground plane), with a dielectric material layer in between, and an ohmic contact, see Fig. 2 [4]. Such disposition could be integrated with a CMOS process since graphene technology is in principle compatible with CMOS circuitry, especially in the back-end-of-the-line, i.e., silicon CMOS chips after the completion of all silicon CMOS processes and metallization/interconnect formation.

Right at the interface between the graphene patch and the dielectric material layer, Surface Plasmon Polariton (SPP) waves are excited. SPP waves are confined EM waves that result from the coupling between surface electric charges at the interface between a metal and a dielectric, and an incident EM wave. The fundamental properties of the SPP wave strongly depend on the conductivity of the graphene layer. In particular, SPP waves on graphene have been observed at frequencies as low as in the terahertz band [5] and can be tuned by material doping [8]. By exploiting the SPP waves in graphene, plasmonic antennas can be developed. The main difference between a metallic antenna and a plasmonic antenna is that the electrical length of the plasmonic antenna is much smaller than that of a metallic antenna, due to the much lower speed of SPP waves in the plasmonic antenna compared to free-space EM waves. These unique properties of graphene allow graphennas to be much more compact than its metallic counterparts, while keeping the same radiation frequency.

However, in order to enable off/on-chip wireless communication, it is necessary to develop circuits to drive the graphenna. These circuits need to operate at the same frequency as the antenna itself. Graphene is ideally suited for this purpose, as the predicted operating frequency of graphene-based RF passive and active devices lies within the same band [1]. Therefore, the development of all-graphene antennas and transceivers is envisaged to facilitate their integration in future GWNoC.

The election of GWC is backed up by the properties and status of the terahertz band. Apart from its high available bandwidth, which leads to increased throughput and low-power communication capabilities, the terahertz band remains unregulated and therefore no license is needed so far in order to operate at such frequencies. Still, from the regulatory perspective, the very high attenuation that terahertz signals suffer in the medium and long range [9] render the signals coming from inside the set negligible in terms of interference. Similarly, other equipment working in the terahertz band should not significantly alter the operation of off/on-chip wireless communication systems; otherwise, graphene-based shielding could be used to minimize such external interferences.

For these reasons, graphennas are expected to enable wireless communication in the terahertz band, with promising applications in on-chip and off-chip communications. While GWC open the door to a huge throughput (hundreds or thousands of Gbps) and simple and low-power transmissions (i.e., impulse radio), it also presents some considerable challenges that are addressed as follows.

A. Antenna Design for Short-range Efficient Communication

Even though the concept of graphene-based plasmonic nano-antennas is still very recent, their radiation properties have already been actively studied by several groups [4], [8], [10], [11]. However, there are still many open research challenges in order to obtain graphennas optimized for on-chip/off-chip wireless communication.

For instance, as previously outlined, the radiation properties of the graphenna greatly depend on the graphene electrical conductivity. Existing works consider a conductivity model for infinitely large two-dimensional graphene sheets [8], [11]. However, as the size of the graphenna is reduced to a few hundreds of nanometers, more accurate models of the frequency-dependent conductivity of graphene nano-ribbons and nano-patches over the terahertz frequency band will need to be investigated. These models will allow the accurate analysis of GWC scenarios using electromagnetic simulation software tools.

Another important challenge concerns the feeding techniques of graphennas in transmission. Most simulation results so far have been obtained assuming pin feed [5] or microstrip feed [11] techniques. In an experimental setup, techniques that require a direct contact with the graphenna might be challenging to implement, due to the small size of the antenna relative to the contacts. Instead, contactless feeding techniques, such as electromagnetic coupling, might be better suited for graphennas in a GWC scenario, allowing the maximization of the antenna radiation efficiency and ensuring impedance adaptation.

Finally, to the best of our knowledge, the literature on graphennas always considered patch and planar dipole antennas to date [4], [8], [11]. In order to obtain antennas with a higher directivity, which may be more useful in a GWC scenario, more sophisticated antenna designs need to be considered. With this purpose, different antenna designs which optimize the spectral and spatial characteristics of the graphenna should be investigated. Moreover, the design of wide-band graphennas (e.g. fractal antennas) and of high-directivity graphennas (e.g., arrays of graphennas) represents another promising avenue in the field of graphenna design.

The evaluation of the radiation properties of graphennas can be done by using a computational electromagnetics simulation tool which solves the Maxwell equations in a custom scenario by means of methods such as the Finite Elements Method or the Method of Moments, amongst others [13]. Such method therefore represents an extremely accurate vision of a real system. This way, the radiation pattern and efficiency characteristics of each new antenna model can be numerically validated.

B. Terahertz Channel Modeling for On-chip and Off-chip Communication

The propagation of EM waves at terahertz frequencies and their interaction with matter pose several challenges in the development of on-chip/off-chip wireless communication. The terahertz band is still one of the least-explored frequency zones of the EM spectrum. The few terahertz channel models existing to date are aimed at characterizing the communication between devices that are several meters away [9] and, thus, may not be suited for the typical transmission ranges in GWNoC (below 2 cm). As a result, some of the properties of this band in the very short range, such as molecular absorption loss and molecular absorption noise [12], remain unknown and have not yet been analyzed in detail. For instance, molecular absorption reduces the usable bandwidth to several transmission windows for distances in the order of a few meters. On the contrary, at chip scale (i.e. millimeters to centimeters) and in a relatively controlled environment, the number of absorbent molecules is limited and, thus, it is possible to think of the entire terahertz band as a single transmission window almost 10 THz wide.

Additionally, the scattering from rough surfaces on the propagation of EM waves as well as the presence of multipath components due to reflections of such waves on the multiple metallic surfaces within the device chassis need to be considered. This can be done by developing a channel model accounting for the path loss (including multipath) and noise of off-chip wireless communications in the terahertz band. Such model would also allow the development of new coding and modulation techniques and the assessment of the available bandwidth in this scenario. Furthermore, the special characteristics of the interaction of the terahertz waves and the environment within a set predicted by the aforementioned model should be numerically validated by simulation.

C. Coding and Modulation Design Space Exploration

The peculiarities of the on-chip/off-chip wireless scenario require to review the coding and modulation schemes employed in classical wireless networks. Energy and chip real estate are two scarce resources in current devices (e.g., smartphones, tablets, laptops). Therefore, the area and energy overhead of a given wireless interconnect with respect to wired interconnects is a critical evaluation factor. Generally, such area and energy figures strongly depend on the coding and modulation employed in the implementation of the physical layer protocols, which determine the architecture of the corresponding transceiver. In this context, the exploration of the coding and modulation design space is a key requirement to implement simple and energy efficient (aiming to go below the pJ/bit barrier) modulations. Another aspect to be taken into account is the presence of dense multipath components due to reflections of the propagating waves in the chip surfaces. Due to this, modulations inherently resistant to multipath need to be inspected with special attention.

Independently of the results of the design space exploration in terms of modulations, Impulse Radio (IR), widely used in Ultra-Wide Band (UWB) systems, stands out as a promising candidate for the implementation of on-chip/off-chip wireless communication. IR consists on the transmission of very short baseband pulses, the length of which determines the bandwidth of such spread spectrum signal [14]. By emitting picosecond long pulses, IR communications in the terahertz band could be implemented. One important advantage of the transceivers required for IR communications is their simplicity and low-power demand (e.g., they can be asynchronous, avoiding the use of power-hungry components such as a phase-locked loop). Furthermore, IR is inherently resistant not only to multipath, but also to collisions. Therefore, this technique would allow the simultaneous transmission of information by different systems inside the set, thereby avoiding the need for complex and costly MAC protocols. Additional practices in this respect, such as Coding Division Multiple Access (CDMA) schemes, should be also considered. Due to the promising conditions of IR communication, the consequences and trade-offs that exist when current IR solutions are upscaled to the terahertz band should be thoroughly considered.

III. PRELIMINARY RESULTS

The signal measured by a receiver in a GWNoC scenario can be mathematically expressed as follows [15]:

$$r(t) = \sum_{\forall k}\sum_{\forall p} \frac{u[k]}{2\pi c d_p} * \mathbf{h}_{rx}(t,\theta_{rx,p},\varphi_{rx,p}) * \delta\left(t-\frac{r_p}{c}\right) * \mathbf{h}_p(t,\theta_p,\varphi_p) * \mathbf{h}_{tx}(t,\theta_{tx,p},\varphi_{tx,p}) * \frac{\mathrm{d}}{\mathrm{d}t}\left(s_{tx}(t)\right) \quad (1)$$

where $u[k]$ is the transmitted signal and p stands for each possible path. The first term takes into account the attenuation due to the propagation through the distance d, $\mathbf{h}_{tx}(t,\theta_p,\varphi_p)$ and $\mathbf{h}_{rx}(t,\theta_p,\varphi_p)$ are vectors taking into account the transfer function the transmitting and receiving antenna. $\mathbf{h}_p(t,\theta_p,\varphi_p)$ is the transfer function matrix of each reflection. Both the characteristic transmit and receive antenna impedances are assumed to be equal.

This expression outlines two important aspects of GWNoC, namely, the time-domain dependence of the transmitted signals and the multipath propagation, which are analyzed next.

A. Time-domain Analysis of Graphennas

To the best of our knowledge, graphennas have been so far studied in the frequency domain [4], [8], [10], [11]. However, in light of not only the potentially wideband nature of the graphennas, but also their very high radiation frequency, it is reasonable to consider a time-domain analysis of the performance of graphennas as well. Indeed, the characterization of antennas in a wide frequency range requires a set of performance metrics different from the ones used in narrowband systems.

For instance, an interesting metric to consider is the temporal response of graphennas. Fig. 3 plots the impulse response of a graphene patch 5 μm long and 1 μm wide at the direction of maximum radiation. The relaxation time of graphene is 2 ps and its chemical potential 0.2 eV. The envelope of its analytic representation is also shown. The response is delayed 1 ps for the sake of clarity. At that instant, an almost instantaneous pulse is observed, followed by an exponential and oscillating decay. The temporal response oscillates at the resonant frequency of the graphenna.

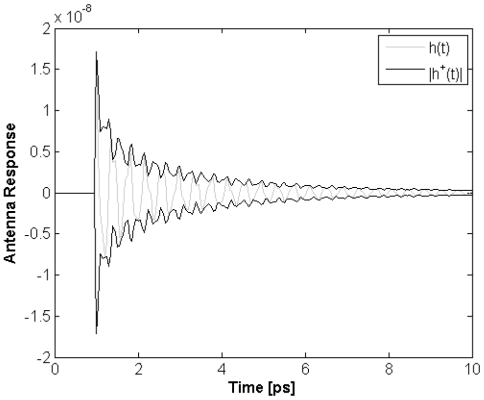

Fig. 3. Impulse response $h(t)$ of a 5x1 μm^2 graphenna with relaxation time 2 ps and chemical potential 0.2 eV. The darker line shows the envelope of the impulse response $|h^{+}(t)|$.

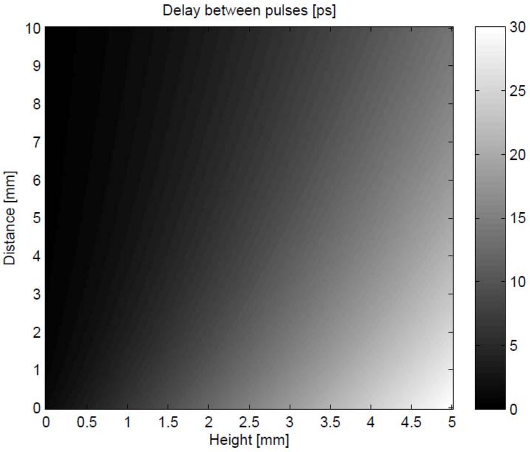

Fig. 4. Delay between the direct and the reflected pulse measured by a graphenna.

B. Multipath Propagation in GWNoC

Another area to consider in the study of a GWNoC scenario is the multipath propagation. Due to multipath, for each information symbol sent, multiple and distorted copies of it reach the receiver in different time instants.

Let us consider two face-to-face graphennas located on a 4 mm-thick silicon substrate. The transmitted signal is a Gaussian pulse centered at 1 THz, with an approximate duration of 1 ps. The receiver antenna measures both the pulse coming from the direct ray as well as its reflection over a flat surface. Fig. 4 shows the delay between both measured pulses as a function of the distance between the antennas and their height over the surface where the electromagnetic wave is reflected. It can be observed that the delay is in the order of tens of picoseconds, which corresponds to tens of pulses.

These results allow the design of techniques to optimize the reception of the transmitted signal, taking into account the effect of the multipath propagation in the achievable data rate.

IV. LONG-TERM VISION

The previous research challenges in terms of channel modeling and modulations schemes for short-range, high-bandwidth and low-power design apply both to wireless communications within a given set as well as to GWNoC.

The application of GWC to on-chip networks may represent an essential breakthrough since the performance bottleneck in multiprocessor systems is foreseen to migrate from the computation to the communication. As the number of cores in a multiprocessor grows, current on-chip network alternatives [16], [17], [18] are rendered insufficient to provide scalable solutions for on-chip communication. Therefore, GWNoC arise as the solution to this need for scalable, flexible and efficient means to interconnect the different cores of a multiprocessor.

GWNoC offer core-level communication as the reduced size of graphennas enables the integration of one or more of them within an individual computing core. Furthermore, since the information transmitted wirelessly can be potentially received by any receiver within the transmission range, GWNoC natively implement broadcast and multicast. Such approach also allows simultaneous transmissions and the creation of reconfigurable communication schemes. Due to all these unique features, a GWNoC will enable not just the alleviation of the latency or power bottlenecks of traditional on-chip networks, but also the devising of novel multiprocessor architectures. As a result, the cost of operations such as data coherency, consistency or synchronization, which represent the main limiting factor in multicore processors, could be significantly reduced and, in a few cases, eliminated.

In summary, solving the previous research challenges will enable the design of both GWNoC-enabled unconventional multiprocessor architectures and a novel communication architecture for the underlying GWNoC.

V. CONCLUSION

Graphene-enabled Wireless Communications will enable the future generation of computer architectures that will emerge from the cross-fertilization of the following fields (i) antennas & propagation (ii) novel nano-materials and (iii) wireless communications. By means of this convergence, computer architectures will be able to implement very high bandwidth wireless communications among the different modules and components of a computer, enabling point-to-point, broadcast, multicast and in general, all-to-all communications. To the best of our knowledge, graphene is the only material able to provide such benefits at such high frequencies. Therefore, it is of key importance to explore the scientific and technical foundations of this new technology, which is envisaged to have both a high industrial and scientific impact in the near future.

In this context, GWC represent a novel application has recently been proposed for graphene, enabling new uses of graphene in the ICT domain and strengthening the position of ICT with respect to ongoing worldwide research in this new material. In the long term, GWC will enable the development of GWNoC, where multi-core processors are equipped with antennas for communications. This novel technology shows potential to cause a paradigm shift in how processors interact between them and with memory, resulting to a radically new multicore architecture. Right now, several multinational large companies (such as Intel, AMD, IBM, NVIDIA and ARM), world leaders in multicore datacenters, are seeking new interconnect technologies. The multi-core market is a multi-billion-dollar business and, if successful, GWNoC represent a window of opportunity to take the lead in this potentially disruptive technological area.

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REFERENCES

[1] A. Geim and K. Novoselov, *The rise of graphene,* Nature materials, vol. 6, no. 3, pp. 18391, 2007.

[2] A. Castro Neto, F. Guinea, N. Peres, K. Novoselov, and A. Geim, *The electronic properties of graphene,* Reviews of Modern Physics, vol. 81, no. 1, pp. 109162, 2009.

[3] J. Kinaret, A. C. Ferrari, V. Falko and J. Kivioja, *Graphene-driven revolutions in ICT and beyond*, Procedia Computer Science, vol. 7, pp. 30-33, 2011.

[4] J. M. Jornet and I. F. Akyildiz, *Graphene-based nano-antennas for electromagnetic nanocommunications in the terahertz band,* in Proc.of 4th European Conference on Antennas and Propagation (EuCAP), Barcelona, 2010.

[5] I. Llatser, C. Kremers, D. N. Chigrin, J. M. Jornet, M. C. Lemme, A. Cabellos-Aparicio and E. Alarcón, *Characterization of Graphene-based Nano-antennas in the Terahertz Band*, in Proc. of the Sixth European Conference on Antennas and Propagation, Prague (Czech Republic), 2012.

[6] S. Abadal, A. Cabellos-Aparicio, E. Alarcón, M. C. Lemme, M. Nemirovsky, *Graphene-enabled Wireless Communication for Massive Multicore Architectures*, in IEEE Communications Magazine, 2012.

[7] S. Abadal, A. Cabellos-Aparicio, J. A. Lázaro, E. Alarcón, J. Solé-Pareta, *Graphene-enabled hybrid architectures for multiprocessors: bridging nanophotonics and nanoscale wireless communication,* in Proceedings of the International Conference in Transparent Optical Networks (ICTON), 2012.

[8] I. Llatser, C. Kremers, A. Cabellos-Aparicio, J. M. Jornet, E. Alarcón, and D. N. Chigrin, *Graphene-based nano-patch antenna for terahertz radiation,* Photonics and Nanostructures - Fundamentals and Applications, 2012.

[9] R. Piesiewicz, T. Kleine-Ostmann, N. Krumbholz, D. Mittleman, M. Koch, J. Schoebel, and T. Kürner, *Short-Range Ultra-Broadband terahertz Communications: Concepts and Perspectives,* IEEE Antennas and Propagation Magazine, vol. 49, no. 6, pp. 2439, 2007.

[10] I. Llatser, C. Kremers, D. N. Chigrin, J. M. Jornet, M. C. Lemme, A. Cabellos-Aparicio and E. Alarcón, *Radiation Characteristics of Tunable Graphennas in the Terahertz Band,* Radioengineering, vol. 21, no. 4, 2012.

[11] J. S. Gomez-Diaz and J. Perruisseau-Carrier, *Microwave to THz Properties of Graphene and Potential Antenna Applications*, International Symposium on Antennas and Propagation, Nagoya (Japan), 2012.

[12] J. M. Jornet and I. F. Akyildiz, *Channel modeling and capacity analysis of electromagnetic wireless nanonetworks in the terahertz band,* IEEE Transactions on Wireless Communications, vol. 10, no. 10, pp. 32113221, 2011.

[13] EM Software and Systems, *FEKO.* Available: http://www.feko.info

[14] M.Z. Win and R. A. Scholtz, *Impulse Radio: How it works*, IEEE Communications Letters, vol. 2, no. 2, pp. 36-38, 1998.

[15] M. Z. Win and R. A. Scholtz. *Impulse radio: How it works,* IEEE Communications Letters, vol. 2, no. 2, pp. 36-38, 1998.

[16] B. S. Feero and P. P. Pande, *Networks-on-Chip in a Three-Dimensional Environment: A Performance Evaluation,* IEEE Transactions on Computers, vol. 58, no. 1, pp. 3245, 2009.

[17] E. Socher and M.-C. F. Chang, *Can RF Help CMOS Processors?* IEEE Communications Magazine, vol. 45, no. 8, pp. 104111, Aug. 2007.

[18] A. Shacham, K. Bergman, and L. P. Carloni, *Photonic networks-on-chip for future generations of chip multiprocessors,* IEEE Transactions on Computers, vol. 57, no. 9, pp. 12461260, 2008.