# Fundamentals of Electromagnetic Nanonetworks in the Terahertz Band

**Josep Miquel Jornet**
Department of Electrical Engineering
University at Buffalo, The State University of New York
Buffalo, NY, USA
jmjornet@buffalo.edu

**Ian F. Akyildiz**
Broadband Wireless Networking Lab
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia, USA
ian@ece.gatech.edu

now
the essence of knowledge
Boston — Delft

**Foundations and Trends® in Networking**

*Published, sold and distributed by:*
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
United States
Tel. +1-781-985-4510
www.nowpublishers.com
sales@nowpublishers.com

*Outside North America:*
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is

J. M. Jornet and I. F. Akyildiz. *Fundamentals of Electromagnetic Nanonetworks in the Terahertz Band*. Foundations and Trends® in Networking, vol. 7, no. 2-3, pp. 77–233, 2012.

*This Foundations and Trends® issue was typeset in LaTeX using a class file designed by Neal Parikh. Printed on acid-free paper.*

ISBN: 978-1-60198-737-2

Full text available at: http://dx.doi.org/10.1561/1300000045

# Foundations and Trends® in Networking

Volume 7, Issue 2-3, 2012

## Editorial Board

# Editorial Scope

## Topics

Foundations and Trends® in Networking publishes survey and tutorial articles in the following topics:

- Modeling and analysis of:
  - Ad hoc wireless networks
  - Sensor networks
  - Optical networks
  - Local area networks
  - Satellite and hybrid networks
  - Cellular networks
  - Internet and web services
- Protocols and cross-layer design
- Network coding
- Energy-efficiency incentives/pricing/utility-based
- Games (co-operative or not)
- Security
- Scalability
- Topology
- Control/Graph-theoretic models
- Dynamics and asymptotic behavior of networks

## Information for Librarians

Foundations and Trends® in Networking, 2012, Volume 7, 4 issues. ISSN paper version 1554-057X. ISSN online version 1554-0588. Also available as a combined paper and online subscription.

Foundations and Trends® in Networking
Vol. 7, No. 2-3 (2012) 77–233

DOI: 10.1561/1300000045

# Fundamentals of Electromagnetic Nanonetworks in the Terahertz Band

Josep Miquel Jornet
Department of Electrical Engineering
University at Buffalo, The State University of New York
Buffalo, NY, USA
jmjornet@buffalo.edu

Ian F. Akyildiz
Broadband Wireless Networking Lab
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia, USA
ian@ece.gatech.edu

# Contents

## Abstract

Nanotechnology is providing a new set of tools to the engineering community to design nanoscale components with unprecedented functionalities. The integration of several nano-components into a single entity will enable the development of advanced nanomachines. Nanonetworks, *i.e.*, networks of nanomachines, will enable a plethora of applications in the biomedical, environmental, industrial and military fields. To date, it is still not clear how nanomachines will communicate. The miniaturization of a classical antenna to meet the size requirements of nanomachines would impose the use of very high radiation frequencies, which would compromise the feasibility of electromagnetic nanonetworks. Therefore, a new wireless technology is needed to enable this paradigm. The objective of this work is to establish the foundations of graphene-enabled electromagnetic communication in nanonetworks. First, novel graphene-based plasmonic nano-antennas are proposed, modeled and analyzed. The obtained results point to the Terahertz Band (0.1-10 THz) as the frequency range of operation of novel nano-antennas. For this, the second contribution in this work is the development of a novel channel model for Terahertz Band communication. In addition, the channel capacity of the Terahertz Band is numerically investigated to highlight the potential of this still-unregulated frequency band. Third, new communication mechanisms for electromagnetic nanonetworks are developed. These include a novel modulation based on the transmission of femtosecond-long pulses, new low-weight codes for channel error prevention in nanonetworks, a novel symbol detection scheme at the nano-receiver, a new energy model for self-powered nanomachines with piezoelectric nano-generators, and a new Medium Access Control protocol tailored to the Terahertz Band. Finally, a one-to-one nano-link is emulated to validate the proposed solutions.


---


J. M. Jornet and I. F. Akyildiz. *Fundamentals of Electromagnetic Nanonetworks in the Terahertz Band*. Foundations and Trends® in Networking, vol. 7, no. 2-3, pp. 77–233, 2012.

DOI: 10.1561/1300000045.

# 1

## Introduction

In 1959, the Nobel laureate physicist Richard Feynman, in his famous speech entitled *"There's Plenty of Room at the Bottom"*, described for the first time how the manipulation of individual atoms and molecules would give rise to more functional and powerful man-made devices. In his talk, he noted that several scaling issues would arise when reaching the nanoscale, which would require the engineering community to rethink the way in which devices are conceived. More than half century later, nanotechnology is providing a new set of tools to the engineering community to control matter at an atomic and molecular scale. At this scale, novel nanomaterials show new properties not observed at the microscopic level. By exploiting these properties, new nanoscale components with unprecedented functionalities are being developed.

Amongst many nanomaterials, graphene, *i.e.*, a one-atom-thick layer of carbon atoms in a honeycomb crystal lattice [88, 30], has recently attracted the attention of the scientific community due to its unique physical, electrical and optical properties. Indeed, despite theoretical research on graphene started back in the 19th century, the experimental discovery of graphene in 2004 by Andre Geim and Konstantin Novoselov, which earned them the Nobel Prize in Physics in

2010, drastically boosted the interest in this unique nanomaterial as well as on its derivatives, *e.g.*, graphene nanoribbons (GNRs), which are thin strips of graphene, and carbon nanotubes (CNTs), which can be analyzed as rolled graphene. Their unique properties enable the development of new types of nano-processors, nano-memories, nano-batteries, and nanosensors, amongst others.

The integration of several of these nano-components in a single entity will enable the development of novel nanomachines. More importantly, similarly to the way in which communication among computers enabled revolutionary applications such as the Internet, by means of communication, nanomachines will be able to overcome their limitations and expand their potential applications [1, 2, 3, 4, 56]. The resulting nanonetworks, *i.e.*, networks of nanomachines, will be able to cover larger areas, to reach unprecedented locations in a non-invasive way, and to perform additional in-network processing.

## 1.1 Applications of Nanonetworks

Nanonetworks are the enabling technology of many long-awaited applications:

- **Biomedical applications:** The nanoscale is the natural domain of molecules, proteins, DNA, organelles and the major components of living cells [85]. As a result, a very large number of applications of nanonetworks is in the biomedical field. For example, nanomaterial-based biological nanosensors [148] can be deployed over (*e.g.*, tattoo-like) or even inside the human body (*e.g.*, a pill or intramuscular injection) to monitor glucose, sodium, and cholesterol [21, 71], to detect the presence of infectious agents [126], or to identify specific types of cancer [129]. A wireless interface between these nanomachines and a micro-device, such as a cellphone or medical equipment, could be used to collect data and to forward it to a healthcare provider.

- **Environmental applications:** Trees, herbs, or bushes, release several chemical composites to the air in order to attract the natural predators of the insects that are attacking them, or to


**Figure 1.1:** The Internet of Nano-Things.

regulate their blooming among different plantations, amongst others [41, 42, 104]. Chemical nanosensors [148] could be used to detect the chemical compounds that are being released and exchanged between plants. Nanonetworks can be build around classical sensor devices which are already deployed in agriculture fields [5]. Other environmental applications include biodiversity control, biodegradation assistance, or air pollution control [109].

- **Industrial and consumer goods applications:** The applications of nanotechnology in the development of new industrial and consumer goods range from flexible and stretchable electronic devices [110] to new functionalized nanomaterials for self-cleaning anti-microbial textiles [128]. In addition, the integration of nanomachines with communication capabilities in every single object will allow the interconnection of almost everything in our daily life, from cooking utensils to every element in our working place, or also the components of every device, enabling what we define as *the Internet of Nano-Things* (see Figure 1.1) [3]. Moreover, as nano-cameras and nano-phones are developed, in a more futuristic approach, the *the Internet of Multimedia Nano-Things* [56] will also become a reality.

- **Military and defense applications:** Advanced nuclear, biological and chemical (NBC) defenses, and sophisticated damage detection systems for civil structures, soldiers' armor and military vehicles, are two examples of the military applications enabled by nanonetworks. For example, a network of nanosensors can be used to detect harmful chemicals and biological weapons with unprecedented accuracy and timeliness, in very different scenarios, from the battle-field (*e.g.*, deployed from an unmanned vehicle and imperceptible by the human eye) to airport lobbies or a conference room (*e.g.*, contained within the wall paint).

## 1.2 Nanomachine Hardware Architecture

There are many challenges in the development of autonomous nanomachines. In Figure 1.2, a conceptual nanomachine architecture is shown. To the best of our knowledge, fully functional nanomachines have not been built to date. However, several solutions for each nano-component have been prototyped and tested:

- **Processing Unit:** Nano-processors are being enabled by the development of tinier FET transistors in different forms. The smallest transistor that has been experimentally tested to date is based on a thin graphene strip made of just 10 by 1 carbon atoms [105]. These transistors are not only smaller, but also able to operate at higher frequencies. The complexity of the operations that a nano-processor will be able to handle directly depend on the number of integrated transistors in the chip, thus, on its total size.

- **Data Storage Unit:** Nanomaterials and new manufacturing processes are enabling the development of single-atom nano-memories, in which the storage of one bit of information requires only one atom [10]. For example, in a magnetic mem-

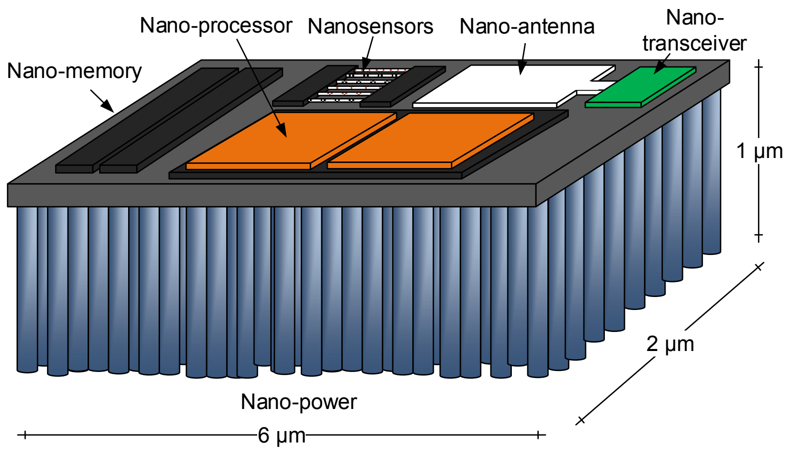


**Figure 1.2:** Nanomachine hardware architecture.

ory [98], atoms are placed over a surface by means of magnetic forces. While these memories are not ready yet for nanomachines, they serve as a starting point. The total amount of information storable in a nano-memory will depend on its dimensions.

- **Power Unit:** Powering nanomachines requires new types of nano-batteries [51, 123] as well as nanoscale energy harvesting systems [138]. One of the most promising techniques relies on the piezoelectric effect seen in zinc oxide nanowires, which are used to convert vibrational energy into electricity. This energy can then be stored in a nano-battery and consumed by the device. The rate at which energy is harvested and the total energy that can be stored in a nano-device depends ultimately on the device size.

- **Sensing Unit:** Physical, chemical and biological nanosensors have been developed by using graphene and other nanomaterials [43, 148]. A nanosensor is not just a tiny sensor, but a device that makes use of the novel properties of nanomaterials to identify and measure new types of events in the nanoscale, such as the physical characteristics of structures just a few nanometers in size, chemical compounds in concentrations as low as one part per billion, or the presence of biological agents such as virus, bacteria or cancerous cells. Their accuracy and timeliness is much higher than those of existing sensors.

- **Communication Unit:** The miniaturization of an antenna to meet the size constraints of nanomachines would impose the use of very high frequencies. This would limit the feasibility of electromagnetic nanonetworks due to the energy limitations of nanomachines. As we will discuss in Chapter 2, nanomaterials can be used to develop new types of nano-antennas as well as nano-transceivers, which can operate at much lower frequencies than miniature metallic antennas. However, these introduce many challenges for the realization of communication in nanonetworks. This sets the starting point of this work.

In addition, there are many crucial challenges in the integration of the different components into a single device. New methods to position and contact different nano-components are currently being developed. Amongst others, DNA scaffolding [62] is one of the most promising techniques. In [62], a procedure to arrange DNA synthesized strands on surfaces made of materials compatible with semiconductor manufacturing equipment has been demonstrated. The positioned DNA nano-structures can serve as scaffolds, or miniature circuit boards, for the precise assembly of the nano-components.

## 1.3 Research Objectives and Outcomes

Due to the hardware peculiarities of nanomachines and the specific applications in which they will be used, nanonetworks are not just a miniaturization of classical wireless networks. There are several challenges in the realization of this new networking paradigm that require new solutions and even to rethink some well-established concepts in communication and network theory. These challenges range from the design of novel nano-antennas, to the characterization of the electromagnetic frequency band in which nano-antennas will radiate or the development of tailored communication mechanisms for nanomachines.

The objective of this work is to establish the foundations of graphene-enabled electromagnetic nanonetworks in the Terahertz Band (0.1-10 THz). The starting point is the development of pioneering graphene-based nano-antennas for communication among nanomachines. The developed analytical models and the related work in graphene-based nano-electronic for RF applications point to the Terahertz Band as the communication band for nanomachines. Motivated by this result, a novel Terahertz Band channel model is developed and the channel capacity of the Terahertz Band is investigated. For very short distances, *i.e.*, much below one meter, the Terahertz Band behaves as a single transmission window which is almost 10 THz wide. Starting from this result, a new set of communication mechanisms for nanonetworks is developed. These include a novel modulation, new channel coding techniques, a novel receiver symbol detection scheme and a medium access control protocol for nanonetworks. In addition, a complete energy model for energy-harvesting self-powered nanomachines is developed to investigate the energy limitations of perpetual nanonetworks. Moreover, an emulation platform is defined and used to validate a one-to-one nano-link between two active nanomachines.

## 1.4 Outline of this Work

The remaining of this work is organized as follows. In Chapter 2, a novel graphene-based plasmonic nano-antenna is proposed, modeled and analyzed. First, the working principle of the antenna is presented. Then, the antenna frequency response is obtained by starting from a novel dynamic complex conductivity model of graphene nanoribbons.

In Chapter 3, a new Terahertz Band channel model is developed, by using radiative transfer theory to obtain formulations for the total path loss and molecular absorption in the Terahertz Band. In addition, the channel capacity is investigated for different power allocation schemes.

In Chapter 4, a femtosecond-long pulse-based modulation and channel access scheme for nanonetworks is proposed. Its performance its analyzed in terms of achievable information rate both for the single-user case and the multi-user case. Novel stochastic models of molecular absorption noise and interference are also developed.

In Chapter 5, a low-weight channel coding technique for error prevention in nanonetworks is developed. First, the impact of the coding weight on the noise and the multi-user interference power is analyzed. Then, the performance of low-weight codes is analytically and numerically investigated.

In Chapter 6, a receiver symbol detection scheme to support the proposed pulse-based modulation and coding techniques is developed. First, the functioning and potential implementation of the CTMA-based detection mechanism is presented. Afterwards, the performance of the proposed scheme is analyzed.

In Chapter 7, a joint energy harvesting and energy consumption model for perpetual nanonetworks in the Terahertz Band is developed. First, an analytical model of novel piezoelectric nano-generators developed and the energy consumption due to communication is quantized. Afterwards, the two processes are jointly analyzed.

In Chapter 8, a physical layer aware MAC protocol for nanonetworks is presented. Its performance is numerically analyzed in terms of energy consumption, end-to-end delay and throughput, by making active use of the developed channel, noise and interference models for nanonetworks in the Terahertz Band.

In Chapter 9, a multi-physics emulation framework is presented. Its implementation is explained in detail. First, the validation of the nano-antenna and the Terahertz Band channel model is performed separately in COMSOL. Afterwards, the integration of COMSOL and Matlab is explained and the complete nano-link is emulated.

Finally, in Chapter 10, the research contributions are summarized and future research directions are identified.

# References


[1] I. F. Akyildiz, F. Brunetti, and C. Blazquez. Nanonetworks: a new communication paradigm. *Computer Networks (Elsevier) Journal*, 52(12):2260–2279, August 2008.

[2] I. F. Akyildiz and J. M. Jornet. Electromagnetic wireless nanosensor networks. *Nano Communication Networks (Elsevier) Journal*, 1(1):3–19, March 2010.

[3] I. F. Akyildiz and J. M. Jornet. The internet of nano-things. *IEEE Wireless Communications Magazine*, 17(6):58–63, December 2010.

[4] I. F. Akyildiz, J. M. Jornet, and M. Pierobon. Nanonetworks: a new frontier in communications. *Communications of the ACM*, 54(11):84–89, November 2011.

[5] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. Wireless sensor networks: a survey. *Computer Networks (Elsevier) Journal*, 38(4):393–422, March 2002.

[6] T. Ando, Y. Zheng, and H. Suzuura. Dynamical conductivity and zero-mode anomaly in honeycomb lattices. *Journal of the Physical Society of Japan*, 71(5):1318–1324, 2002.

[7] J. G. Andrews, R. K. Ganti, M. Haenggi, N. Jindal, and S. Weber. A primer on spatial modeling and analysis in wireless networks. *IEEE Communications Magazine*, 48(11):156 –163, November 2010.

[8] C. A. Balanis. *Antenna theory: analysis and design.* John Wiley & Sons, 2005.

[9] A. Barbieri, F. Pancaldi, and G.M. Vitetta. A novel ultrawideband system for multiuser data communications. *IEEE Transactions on Wireless Communications*, 10(12):4324–4333, 2011.

[10] R Bennewitz, J N Crain, A Kirakosian, J-L Lin, J L McChesney, D Y Petrovykh, and F J Himpsel. Atomic scale memory at a silicon surface. *Nanotechnology*, 13(4):499–502, 2002.

[11] F. Box. Utilization of atmospheric transmission losses for interference-resistant communications. *IEEE Transactions on Communications*, 34(10):1009–1015, October 1986.

[12] W. Brown, B. Wallin, D. Lesniewski, D. Gooding, and J. Martin. The experimental determination of on-off keying laser communications probability models and a comparison with theory. *Proc*, pages 61050U–61050U–8, 2006.

[13] P. Burke, S. Li, and Z. Yu. Quantitative theory of nanowire and nanotube antenna performance. *IEEE Transactions on Nanotechnology*, 5(4):314–334, July 2006.

[14] P. Cardieri. Modeling interference in wireless ad hoc networks. *IEEE Communications Surveys and Tutorials*, 12(4):551–572, 2010.

[15] COMSOL Multiphysics Simulation Software. COMSOL.

[16] G. Deligeorgis, F. Coccetti, G. Konstantinidis, and R. Plana. Radio frequency signal detection by ballistic transport in y-shaped graphene nanoribbons. *Applied Physics Letters*, 101(1):013502, 2012.

[17] G. Deligeorgis, M. Dragoman, D. Neculoiu, D. Dragoman, G. Konstantinidis, A. Cismaru, and R. Plana. Microwave propagation in graphene. *Applied Physics Letters*, 95(7):073107, 2009.

[18] S. Dolinar, D. Divsalar, J. Hamkins, and F. Pollara. Capacity of ppm on gaussian and webb channels. In *Information Theory, 2000. Proceedings. IEEE International Symposium on*, page 410, 2000.

[19] J. Dorfmualler, R. Vogelgesang, W. Khunsin, C. Rockstuhl, C. Etrich, and K. Kern. Plasmonic nanowire antennas: Experiment, simulation, and theory. *Nano Letters*, 10(9):3596–3603, 2010.

[20] M. Dragoman, A. A. Muller, D. Dragoman, F. Coccetti, and R. Plana. Terahertz antenna based on graphene. *Journal of Applied Physics*, 107:104313–3, 2010.

[21] J. Matthew Dubach, Daniel I. Harjes, and Heather A. Clark. Fluorescent ion-selective nanosensors for intracellular analysis with improved lifetime and size. *Nano Letters*, 7(6):1827–2831, 2007.

[22] A A Dubinov, V Ya Aleshkin, V Mitin, T Otsuji, and V Ryzhii. Terahertz surface plasmons in optically pumped graphene structures. *Journal of Physics: Condensed Matter*, 23(14):145302, 2011.

[23] T. W. Ebbesen, H. J. Lezec, H. Hiura, J. W. Bennett, H. F. Ghaemi, and T. Thio. Electrical conductivity of individual carbon nanotubes. *Nature*, 382(6582):54–56, July 1996.

[24] R. Esteban, T. V. Teperik, and J. J. Greffet. Optical patch antennas for single photon emission using surface plasmon resonances. *Physical Review Letters*, 104:026802, January 2010.

[25] L. Falkovsky and S. Pershoguba. Optical far-infrared properties of a graphene monolayer and multilayer. *Physical Review B*, 76:1–4, 2007.

[26] L. Falkovsky and A. A. Varlamov. Space-time dispersion of graphene conductivity. *The European Physical Journal B*, 56:281–284, 2007.

[27] J. Federici and L. Moeller. Review of terahertz and subterahertz wireless communications. *Journal of Applied Physics*, 107(11):111101, 2010.

[28] I. M. Filanovsky and P. N. Matkhanov. Synthesis of reactance networks shaping a quasi-rectangular pulse. *IEEE Transactions on Circuits and Systems II: Express Briefs*, 52(5):242 – 245, may 2005.

[29] Y. Gao and Z. L. Wang. Electrostatic potential in a bent piezoelectric nanowire. the fundamental theory of nanogenerator and nanopiezotronics. *Nano Letters*, 7(8):2499–2505, 2007.

[30] A. K. Geim and K. S. Novoselov. The rise of graphene. *Nature Materials*, 6(3):183–191, March 2007.

[31] A. Gerosa, S. Solda, A. Bevilacqua, D. Vogrig, and A. Neviani. An energy-detector for noncoherent impulse-radio UWB receivers. *IEEE Transactions on Circuits and Systems I: Regular Papers*, 56(5):1030 – 1040, May 2009.

[32] A. Goldsmith. *Wireless Communications*. Cambridge University Press, New York, NY, USA, 2005.

[33] R. M. Goody and Y. L. Yung. *Atmospheric Radiation: Theoretical basis*. Oxford University Press, 2 edition, 1989.

[34] J. Gummeson, S. S. Clark, K. Fu, and D. Ganesan. On the limits of effective hybrid micro-energy harvesting on mobile CRFID sensors. In *Proc. of the 8th ACM international conference on Mobile systems, applications, and services, MobiSys*, 2010.

[35] V. P. Gusynin and S. G. Sharapov. Transport of dirac quasiparticles in graphene: hall and optical conductivities. *Physical Review B*, 73:245411, June 2006.

[36] V. P. Gusynin, S. G. Sharapov, and J. P. Carbotte. AC conductivity of graphene: from tight-binding model to 2+1-dimensional quantum electrodynamics. *International Journal of Modern Physics B*, 21:4611, 2007.

[37] I. Guvenc and H. Arslan. On the modulation options for uwb systems. In *IEEE Military Communications Conference (MILCOM)*, volume 2, pages 892–897 Vol.2, 2003.

[38] G. W. Hanson. Fundamental transmitting properties of carbon nanotube antennas. *IEEE Transactions on Antennas and Propagation*, 53(11):3426–3435, November 2005.

[39] G. W. Hanson. Dyadic Green's functions and guided surface waves for a surface conductivity model of graphene. *Journal of Applied Physics*, 103(6):064302, 2008.

[40] G. W. Hanson. Dyadic Green's functions for an anisotropic, non-local model of biased graphene. *IEEE Transactions on Antennas and Propagation*, 56(3):747–757, March 2008.

[41] M. Heil and J. C. Silva Bueno. Within-plant signaling by volatiles leads to induction and priming of an indirect plant defense in nature. *Proceedings of the National Academy of Sciences*, 104(13):5467–5472, 2007.

[42] M. Heil and J. Ton. Long-distance signalling in plant defence. *Trends in Plant Science*, 13(6):264–272, 2008.

[43] C. Hierold, A. Jungen, C. Stampfer, and T. Helbling. Nano electromechanical sensors based on carbon nanotubes. *Sensors and Actuators A: Physical*, 136(1):51–61, 2007.

[44] F. Hipolito, A. J. Chaves, R. M. Ribeiro, M. I. Vasilevskiy, Vitor M. Pereira, and N. M. R. Peres. Enhanced optical dichroism of graphene nanoribbons. *Phys. Rev. B*, 86:115430, September 2012.

[45] J. Horng, C.-F. Chen, B. Geng, C. Girit, Y. Zhang, Z. Hao, H. A. Bechtel, M. Martin, A. Zettl, M. F. Crommie, Y. Ron Shen, and Feng Wang. Drude conductivity of dirac fermions in graphene. *Physical Review B*, 83:165113, April 2011.

[46] K.-C. Huang and Z. Wang. Terahertz terabit wireless communication. *IEEE Microwave Magazine*, 12(4):108–116, June 2011.

[47] P. A. Humblet and M. Azizoglu. On the bit error rate of lightwave systems with optical amplifiers. *Journal of Lightwave Technology*, 9(11):1576 –1582, November 1991.

[48] IEEE. 802.15.4a: wireless medium access control (MAC) and physical layer (PHY) specifications for low-rate wireless personal area networks (WPANs). Amendment 1: add alternate physical.

[49] IEEE 802.15 WPAN Study Group 100 Gbit/s Wireless (SG100G).

[50] M. Jablan, H. Buljan, and M. Soljačić. Plasmonics in graphene at infrared frequencies. *Physical Review B*, 80:245435, December 2009.

[51] L. Ji, Z. Tan, T. Kuykendall, E. J. An, Y. Fu, V. Battaglia, and Y. Zhang. Multilayer nanoassembly of sn-nanopillar arrays sandwiched between graphene layers for high-capacity lithium storage. *Energy Environ. Sci.*, 4:–, 2011.

[52] 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*, April 2010.

[53] 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*, 10(10):3211–3221, October 2011.

[54] J. M. Jornet and I. F. Akyildiz. Information capacity of pulse-based wireless nanosensor networks. In *Proc. of the 8th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, SECON*, June 2011.

[55] J. M. Jornet and I. F. Akyildiz. Low-weight channel coding for interference mitigation in electromagnetic nanonetworks in the terahertz band. In *Proc. of IEEE International Conference on Communications, ICC*, June 2011.

[56] J. M. Jornet and I. F. Akyildiz. The internet of multimedia nanothings. *Nano Communication Networks (Elsevier) Journal*, 3(4):242–251, December 2012.

[57] J. M. Jornet and I. F. Akyildiz. Joint energy harvesting and communication analysis for perpetual wireless nanosensor networks in the terahertz band. *IEEE Transactions on Nanotechnology*, 11(3):570–580, 2012.

[58] J. M. Jornet and I. F. Akyildiz. Graphene-based plasmonic nano-antenna for terahertz band communication in nanonetworks. *to appear in IEEE JSAC, Special Issue on Emerging Technologies for Communications*, 2013.

[59] J. M. Jornet, J. Capdevila Pujol, and J. Sole-Pareta. PHLAME: A physical layer aware mac protocol for electromagnetic nanonetworks in the terahertz band. *Nano Communication Networks*, 3(1):74 – 81, 2012.

[60] L. Ju, B. Geng, J. Horng, C. Girit, M. martin, Z. Hao, H.A. Bechtel, X. Liang, A. Zettl, Y. R. Shen, and F. Wang. Graphene plasmonics for tunable terahertz metamaterials. *Nature Nanotechnology*, 6:630–634, September 2011.

[61] P. V. Kamat. Harvesting photons with carbon nanotubes. *Nano Today*, 1(4):20–27, 2006.

[62] R. J. Kershner, L. D. Bozano, C. M. Micheel, A. M. Hung, A. R. Fornof, J. N. Cha, C. T. Rettner, M. Bersani, J. Frommer, P. W. K. Rothemund, and G. M. Wallraff. Placement and orientation of individual DNA shapes on lithographically patterned surfaces. *Nature Nanotechnology*, 4(9):557–561, August 2009.

[63] T. Kleine-Ostmann and T. Nagatsuma. A review on terahertz communications research. *Journal of Infrared, Millimeter and Terahertz Waves*, 32:143–171, 2011.

[64] L. Kleinrock. *Queueing Systems. Volume 1: Theory*. Wiley-Interscience, 1975.

[65] W Knap, F Teppe, N Dyakonova, D Coquillat, and J Lusakowski. Plasma wave oscillations in nanometer field effect transistors for terahertz detection and emission. *Journal of Physics: Condensed Matter*, 20(38):384205, 2008.

[66] M. Koch. Terahertz communications: A 2020 vision. In Robert Miles, Xi-Cheng Zhang, Heribert Eisele, and Arunas Krotkus, editors, *Terahertz Frequency Detection and Identification of Materials and Objects*, volume 19 of *NATO Security through Science Series*, pages 325–338. Springer, 2007.

[67] F. H. L. Koppens, D. E. Chang, and F. J. Garcia de Abajo. Graphene plasmonics: a platform for strong light matter interactions. *Nano Letters*, 11(8):3370–3377, August 2011.

[68] F.S. Lee and A.P. Chandrakasan. A 2.5 nJ/bit 0.65 V pulsed UWB receiver in 90 nm CMOS. *IEEE Journal of Solid-State Circuits*, 42(12):2851–2859, December 2007.

[69] S.H. Lee, M. Choi, T. Kim, S. Lee, M. Liu, X. Yin, H.K. Choi, S.S. Lee, C. Choi, S. Choi, X. Zhang, and B. Min. Switching terahertz waves with gate-controlled active graphene metamaterials. *Nat Mater*, 2012.

[70] J. Lei, R. Yates, and L. Greenstein. A generic model for optimizing single-hop transmission policy of replenishable sensors. *IEEE Transactions on Wireless Communications*, 8(2):547–551, 2009.

[71] J. Li, T. Peng, and Y. Peng. A cholesterol biosensor based on entrapment of cholesterol oxidase in a silicic sol-gel matrix at a prussian blue modified electrode. *Electroanalysis*, 15(12):1031–1037, 2003.

[72] J.S. Lim, C.B. Kim, J.S. jang, H.S. Lee, Y.H. jung, J.H. Kim, S.B. Park, B.H. Lee, and M.S. Lee. Design of a subwavelength patch antenna using metamaterials. In *38th European Microwave Conference, EuMC*, pages 1246 –1249, October 2008.

[73] Y.-Ming Lin, A. Valdes-Garcia, S.-J Han, D. B. Farmer, I. Meric, Y. Sun, Y. Wu, C. Dimitrakopoulos, A. Grill, P. Avouris, and K. A. Jenkins. Wafer-scale graphene integrated circuit. *Science*, 332(6035):1294–1297, 2011.

[74] R.-S. Liu, K.-W. Fan, Z. Zheng, and P. Sinha. Perpetual and fair data collection for environmental energy harvesting sensor networks. *IEEE/ACM Transactions on Networking*, 19(4):947–960, August 2011.

[75] I. Llatser, C. Kremers, A. Cabellos-Aparicio, J. M. Jornet, E. Alarcon, and D. N. Chigrin. Graphene-based nano-patch antenna for terahertz radiation. *Photonics and Nanostructures - Fundamentals and Applications*, 10(4):353–358, October 2012.

[76] C. Manolatou and F. Rana. Subwavelength nanopatch cavities for semiconductor plasmon lasers. *IEEE Journal of Quantum Electronics*, 44(5):435–447, May 2008.

[77] I. Llatser Marti, C. Kremers, A. Cabellos-Aparicio, J. M. Jornet, E. Alarcon, and D. N. Chigrin. Scattering of terahertz radiation on a graphene-based nano-antenna. *AIP Conference Proceedings of The Fourth International Workshop on Theoretical and Computational Nanophotonics, TaCoNa*, 1398(1):144–146, 2011.

[78] B. Medepally, N.B. Mehta, and C.R. Murthy. Implications of energy profile and storage on energy harvesting sensor link performance. In *Proc. of IEEE Global Telecommunications Conference, GLOBECOM*, 2009.

[79] P.P. Mercier, M. Bhardwaj, D.C. Daly, and A.P. Chandrakasan. A low-voltage energy-sampling ir-uwb digital baseband employing quadratic correlation. *IEEE Journal of Solid-State Circuits*, 45(6):1209 –1219, June 2010.

[80] S. A. Mikhailov. Theory of the giant plasmon-enhanced second-harmonic generation in graphene and semiconductor two-dimensional electron systems. *Physical Review B*, 84:045432, July 2011.

[81] S. A. Mikhailov and K. Ziegler. New electromagnetic mode in graphene. *Physical Review Letters*, 99:1–4, 2007.

[82] S. A. Mikhailov and K. Ziegler. Nonlinear electromagnetic response of graphene: frequency multiplication and the self-consistent-field effects. *Journal of Physics: Condensed Matter*, 20:384204, 2008.

[83] R.F. Mills and G.E. Prescott. A comparison of various radiometer detection models. *IEEE Transactions on Aerospace and Electronic Systems*, 32(1):467 –473, jan. 1996.

[84] P. Mukherjee and B. Gupta. Terahertz (THz) Frequency Sources and Antennas-A Brief Review. *International Journal of Infrared and Millimeter Waves*, 29(12):1091–1102, December 2008.

[85] D. L. Nelson and M. M. Cox. *Lehninger Principles of Biochemistry*. W. H. Freeman Company, May 2008.

[86] A. Yu. Nikitin, F. Guinea, F. J. Garcia-Vidal, and L. Martin-Moreno. Edge and waveguide terahertz surface plasmon modes in graphene microribbons. *Physical Review B*, 84:161407, October 2011.

[87] D. Niyato, E. Hossain, M.M. Rashid, and V.K. Bhargava. Wireless sensor networks with energy harvesting technologies: a game-theoretic approach to optimal energy management. *IEEE Wireless Communications*, 14(4):90 –96, August 2007.

[88] K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang, S. V. Dubonos, I. V. Grigorieva, and A. A. Firsov. Electric Field Effect in Atomically Thin Carbon Films. *Science*, 306(5696):666–669, 2004.

[89] I. Oppermann, M. Hamalainen, and J. Linatti, editors. *UWB: Theory and Applications*. Wiley, 2004.

[90] T. Otsuji, S. Boubanga Tombet, A. Satou, M. Ryzhii, and V. Ryzhii. Terahertz-wave generation using graphene - toward new types of terahertz lasers. *IEEE Journal of Selected Topics in Quantum Electronics*, 19(1):8400209, 2013.

[91] T Otsuji, S A Boubanga Tombet, A Satou, H Fukidome, M Suemitsu, E Sano, V Popov, M Ryzhii, and V Ryzhii. Graphene-based devices in terahertz science and technology. *Journal of Physics D: Applied Physics*, 45(30):303001, 2012.

[92] T. Otsuji, H. Karasawa, T. Watanabe, T. Suemitsu, M. Suemitsu, E. Sano, W. Knap, and V. Ryzhii. Emission of terahertz radiation from two-dimensional electron systems in semiconductor nano-heterostructures. *Comptes Rendus Physique*, 11(7-8):421–432, August 2010.

[93] T. Otsuji, T. Komori, T. Watanabe, T. Suemitsu, D. Coquillat, and W. Knap. Plasmon-resonant microchip emitters and detectors for terahertz sensing and spectroscopic applications. In *Proc. of SPIE*, pages 767102–767102–12, 2010.

[94] A. N. Pal and A. Ghosh. Ultralow noise field-effect transistor from multilayer graphene. *Applied Physics Letters*, 95(8), 2009.

[95] L. Palfalvi, J. A. Fulop, G. Almasi, and J. Hebling. novel setups for extremely high power single-cycle terahertz pulse generation by optical rectification. *Applied Physics Letters*, 92(17):171107, 2008.

[96] M.F. Pantoja, D.H. Werner, P.L. Werner, and A.R. Bretones. TDIE modeling of carbon nanotube dipoles at microwave and terahertz bands. *IEEE Antennas and Wireless Propagation Letters*, 9:32–35, 2010.

[97] A. Papoulis and S. U. Pillai. *Probability, Random Variables and Stochastic Processes*. McGraw-Hill, 2002.

[98] S. P. Parkin, M. Hayashi, and L. Thomas. Magnetic domain-wall racetrack memory. *Science*, 320(5873):190–194, 2008.

[99] D. Pech, M. Brunet, H. Durou, P. Huang, V. Mochalin, Y. Gogotsi, P.L. Taberna, and P. Simon. Ultrahigh-power micrometre-sized supercapacitors based on onion-like carbon. *Nature nanotechnology*, 5(9):651–655, September 2010.

[100] N. Peres, A. Castro Neto, , and F. Guinea. Conductance quantization in mesoscopic graphene. *Physical Review B*, 73(19):195411, May 2006.

[101] J. Perruisseau-Carrier. Graphene for antenna applications: Opportunities and challenges from microwaves to thz. *submitted for journal publication*, 2012.

[102] R. Piesiewicz, T. Kleine-Ostmann, N. Krumbholz, D. Mittleman, M. Koch, and T. Kurner. Terahertz characterisation of building materials. *Electronics Letters*, 41(18):1002–1004, September 2005.

[103] R. Piesiewicz, T. Kleine-Ostmann, N. Krumbholz, D. Mittleman, M. Koch, J. Schoebel, and T. Kurner. Short-range ultra-broadband terahertz communications: concepts and perspectives. *IEEE Antennas and Propagation Magazine*, 49(6):24–39, December 2007.

[104] C. M. J. Pieterse and M. Dicke. Plant interactions with microbes and insects: from molecular mechanisms to ecology. *Trends in Plant Science*, 12(12):564–569, 2007.

[105] L. A. Ponomarenko, F. Schedin, M. I. Katsnelson, R. Yang, E. W. Hill, K. S. Novoselov, and A. K. Geim. Chaotic Dirac billiard in graphene quantum dots. *Science*, 320(5874):356–358, April 2008.

[106] S. Priebe, C. Jastrow, M. Jacob, T. Kleine-Ostmann, T. Schrader, and T. Kurner. Channel and propagation measurements at 300 GHz. *IEEE Transactions on Antennas and Propagation*, 59(5):1688 –1698, May 2011.

[107] R.C. Qiu, H. Liu, and X. Shen. Ultra-wideband for multiple access communications. *IEEE Communications Magazine*, 43(2):80–87, 2005.

[108] E.A. Ratzer and D.J.C. MacKay. Sparse low-density parity-check codes for channels with cross-talk. In *Proc. of IEEE Information Theory Workshop*, pages 127–130, March 2003.

[109] J. Riu, A. Maroto, and F. X. Rius. Nanosensors in environmental analysis. *Talanta*, 69(2):288–301, 2006.

[110] J.A. Rogers. Materials and mechanics for stretchable electronics-from electronic eye cameras to conformal brain monitors. In *International Solid-State Sensors, Actuators and Microsystems Conference*, pages 1602–1603, June 2009.

[111] L.S. Rothman, I.E. Gordon, A. Barbe, D. Chris Benner, P.F. Bernath, M.Birk, V. Boudon, L.R. Brown, and A.Campargue. The HITRAN 2008 molecular spectroscopic database. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 110(9-10):533–572, June 2009.

[112] S. Roundy, P. K. Wright, and J. M. Rabaey. *Energy Scavenging for Wireless Sensor Networks: With Special Focus on Vibrations.* Kluwer Academic Publishers, Norwell, MA, USA, 2004.

[113] K.-I. Sasaki, K. Kato, Y. Tokura, K. Oguri, and T. Sogawa. Theory of optical transitions in graphene nanoribbons. *Physical Review B*, 84:085458, August 2011.

[114] B. Sensale-Rodriguez, R. Yan, M. M. Kelly, T. Fang, K. Tahy, W. S. Hwang, D. Jena, L. Liu, and H. G. Xing. Broadband graphene terahertz modulators enabled by intraband transitions. *Nature Communications*, 3:780+, April 2012.

[115] V. Sharma, U. Mukherji, V. Joseph, and S. Gupta. Optimal energy management policies for energy harvesting sensor nodes. *IEEE Transactions on Wireless Communications*, 9(4):1326–1336, 2010.

[116] E. Shih, S.-H. Cho, N. Ickes, R. Min, A. Sinha, A. Wang, and A. Chandrakasan. Physical layer driven protocol and algorithm design for energy-efficient wireless sensor networks. In *Proc. of the ACM International Conference on Mobile Computing and Networking, MOBICOM*, pages 272–287, 2001.

[117] G. Ya. Slepyan, S. A. Maksimenko, A. Lakhtakia, O. Yevtushenko, and A. V. Gusakov. Electrodynamics of carbon nanotubes: Dynamic conductivity, impedance boundary conditions, and surface wave propagation. *Phys. Rev. B*, 60:17136–17149, December 1999.

[118] G.Ya. Slepyan, M.V. Shuba, A.M. Nemilentsau, and S.A. Maksimenko. Electromagnetic theory of nanodimensional antennas for terahertz, infrared and optical regimes. In *12th International Conference on Mathematical Methods in Electromagnetic Theory, MMET*, pages 118–123, July 2008.

[119] S. Smaili, V. Singal, and Y. Massoud. On the effect of width of metallic armchair graphene nanoribbons in plasmonic waveguide applications. In *7th IEEE International Conference on Nano/Micro Engineered and Molecular Systems (NEMS)*, pages 623 –626, March 2012.

[120] R. Sordan, F. Traversi and V. Russo. Logic gates with a single graphene transistor. *Applied Physics Letters*, 94:073305, 2009.

[121] E.S. Sousa. Performance of a spread spectrum packet radio network link in a poisson field of interferers. *IEEE Transactions on Information Theory*, 38(6):1743 –1754, November 1992.

[122] T. Stauber, N. M. R. Peres, and A. K. Geim. Optical conductivity of graphene in the visible region of the spectrum. *Physical Review B*, 78:085432, August 2008.

[123] M. D. Stoller, S. Park, Y. Zhu, J. An, and R. S. Ruoff. Graphene-based ultracapacitors. *Nano Letters*, 8(10):3498–3502, October 2008.

[124] S. Sudevalayam and P. Kulkarni. Energy harvesting sensor nodes: survey and implications. *IEEE Communications Surveys Tutorials*, 13(3):443 – 461, 2011.

[125] J. Tabor. Noise reduction using low weight and constant weight coding techniques. Technical report, MIT, Cambridge, MA, USA, 1990.

[126] P. Tallury, A. Malhotra, L. M. Byrne, and S. Santra. Nanobioimaging and sensing of infectious diseases. *Advanced Drug Delivery Reviews*, 62(4-5):424–437, March 2010.

[127] M. Tamagnone, J. S. Gomez-Diaz, J. R. Mosig, and J. Perruisseau-Carrier. Reconfigurable terahertz plasmonic antenna concept using a graphene stack. *Applied Physics Letters*, 101(21):214102, 2012.

[128] D. Tessier, I. Radu, and M. Filteau. Antimicrobial fabrics coated with nano-sized silver salt crystals. *NSTI Nanotech*, 1:762–764, 2005.

[129] I. E. Tothill. Biosensors for cancer markers diagnosis. *Seminars in Cell & Developmental Biology*, 20(1):55–62, 2009.

[130] A. Vakil and N. Engheta. Transformation optics using graphene. *Science*, 332(6035):1291–1294, June 2011.

[131] L. Vicarelli, M. S. Vitiello, D. Coquillat, A. Lombardo, A. C. Ferrari, W. Knap, M. Polini, V. Pellegrini, and A. Tredicucci. Graphene field-effect transistors as room-temperature terahertz detectors. *Nature Materials*, 11:865–871, October 2012.

[132] M. S. Vitiello, D. Coquillat, L. Viti, D. Ercolani, F. Teppe, A. Pitanti, F. Beltram, L. Sorba, W. Knap, and A. Tredicucci. Room-temperature terahertz detectors based on semiconductor nanowire field-effect transistors. *Nano Letters*, 12(1):96–101, 2012.

[133] A. Wallwater, M. Gorlatova and G. Zussman. Networking low-power energy harvesting devices: Measurements and algorithms. In *Proc. of the International Conference on Computer Communication, INFOCOM*, Shanghai, China, April 2011.

[134] H. Wang, A. Hsu, K. K. Kim, J. Kong, and T. Palacios. Gigahertz ambipolar frequency multiplier based on cvd graphene. In *Proc. of IEDM10*, pages 572–575, 2010.

[135] H. Wang, A. Hsu, J. Wu, J. Kong, and T. Palacios. Graphene-based ambipolar rf mixers. *IEEE Electron Device Letters*, 31:906Ű908, 2010.

[136] H. Wang, D. Nezich, J. Kong, and T. Palacios. Graphene frequency multipliers. *IEEE Electron Device Letters*, 30(5):547 –549, May 2009.

[137] Y. Wang, M.C. Vuran, and S. Goddard. Stochastic analysis of energy consumption in wireless sensor networks. In *Proc. of the 7th Annual IEEE Communications Society Conference on Sensor Mesh and Ad Hoc Communications and Networks, SECON*, pages 1–9, June 2010.

[138] Z. L. Wang. Towards self-powered nanosystems: from nanogenerators to nanopiezotronics. *Advanced Functional Materials*, 18(22):3553–3567, 2008.

[139] M. Weisenhorn and W. Hirt. Uncoordinated rate-division multiple-access scheme for pulsed uwb signals. *IEEE Transactions on Vehicular Technology*, 54(5):1646–1662, September 2005.

[140] D.D. Wentzloff, F.S. Lee, D.C. Daly, M. Bhardwaj, P.P. Mercier, and A.P. Chandrakasan. Energy efficient pulsed-UWB CMOS circuits and systems. In *Proc. of IEEE International Conference on Ultra-Wideband*, pages 282 –287, September 2007.

[141] P.R. West, S. Ishii, G.V. Naik, N.K. Emani, V.M. Shalaev, and A. Boltasseva. Searching for better plasmonic materials. *Laser & Photonics Reviews*, 4(6):795–808, 2010.

[142] M.Z. Win, P.C. Pinto, and L.A. Shepp. A mathematical theory of network interference and its applications. *Proceedings of the IEEE*, 97(2):205 –230, February 2009.

[143] S. Xu, B. J. Hansen, and Z. L. Wang. Piezoelectric-nanowire-enabled power source for driving wireless microelectronics. *Nature Communications*, 1(7):1–5, October 2010.

[144] S. Xu, Y. Qin, C. Xu, Y. Wei, R. Yang, and Z. L. Wang. Self-powered nanowire devices. *Nature Nanotechnology*, 5:366–373, 2010.

[145] H. Yan, X. Li, B. Chandra, G. Tulevski, Y. Wu, M. Freitag, W. Zhu, P. Avouris, and F. Xia. Tunable infrared plasmonic devices using graphene/insulator stacks. *Nature Nanotechnology*, 7(5):330–4, 2012.

[146] K. Yasuko and S. Takamasa. Terahertz-wave propagation model. *Journal of the National Institute of Information and Communications Technology*, 55(1):73–77, 2008.

[147] K.-L. Yeh, M. C. Hoffmann, J. Hebling, and K. A. Nelson. Generation of 10 mu j ultrashort terahertz pulses by optical rectification. *Applied Physics Letters*, 90(17):171121, 2007.

[148] C. R. Yonzon, D. A. Stuart, X. Zhang, A. D. McFarland, C/ L. Haynes, and R. P. Van Duyne. Towards advanced chemical and biological nanosensors-an overview. *Talanta*, 67(3):438–448, 2005.

[149] X.P. Zhou, I. Oka, and C. Fujiwara. Network performance of time spread ppm/cdma systems. In *Proc of 'Communications on the Move': Singapore ICCS/ISITA*, pages 929–933, 1992.

[150] T. Zhu, Z. Zhong, Y. Gu, T. He, and Z.-L. Zhang. Leakage-aware energy synchronization for wireless sensor networks. In *Proc. of the 7th ACM international conference on Mobile systems, applications, and services, MobiSys*, pages 319–332, 2009.

[151] Z. Zou, D. Sarmiento Mendoza, P. Wang, Q. Zhou, J. Mao, F. Jonsson, H. Tenhunen, and L.-R. Zheng. A low-power and flexible energy detection IR-UWB receiver for RFID and wireless sensor networks. *IEEE Transactions on Circuits and Systems I: Regular Papers*, 58:1470–1482, 2011.