

Energy Harvesting Communication Networks: Optimization and Demonstration (The E-CROPS Project)

Erol Gelenbe¹, David Gesbert², Deniz Gunduz¹, Haluk Klah³ and Elif Uysal-Biyikođlu³

¹Department of Electrical Engineering, Imperial College London, London, UK

²Mobile Communications Department, Institut Eurecom, Biot, France

³Dept of Electrical and Electronic Engineering, Middle East Technical University, Ankara, Turkey

Abstract—We describe the new European project E-CROPS which was ranked first in the 2012 CHIST-ERA competition. This project has begun its work in February 2013 to develop a system-wide approach to using energy harvesting and smart energy management technologies in communication and mobile devices. The project will examine energy-dependent fundamental limits of communications, together with the timely harvesting, storage and delivery of energy to the computing and communication units of these devices, to achieve an optimal balance between the quality of service, performance, and efficient usage of energy. E-CROPS will combine theoretical modelling and performance analysis with experimental demonstrations bringing together four collaborating teams from France (EURECOM), Spain (CTTC), Turkey (METU) and the UK (Imperial College London).

Index Terms—energy harvesting; energy packet networks; Markov models and decision processes; queuing networks; G-networks

I. INTRODUCTION

With the increasing proportion of information and communication technologies (ICT) within the global carbon footprint, energy efficiency in acquisition, processing and distribution of information over wired and wireless networks has become a major research problem [1]–[3]. Generally ICT is predicted to increase its energy consumption by 4% per year till 2020 [4], also because it increasingly penetrates all areas of human activity and uses new technologies such as cloud computing and web search [5]. Communication systems already take up some 25% of the energy used by ICT, while the exponential increase in processing power and density of mobile devices has not yet been matched by improvements in battery technology. Furthermore, network attacks and resulting defense are very common [6], and cause even

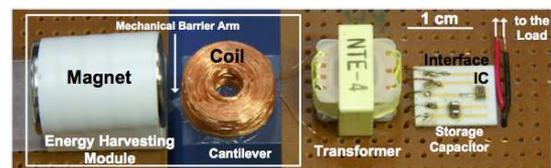


Fig. 1. The energy harvesting system structure.

further energy consumption. Hence, both the communication lifetime and physical size of communication nodes are limited by battery size. While microelectronics is becoming more efficient in energy usage versus the amount of work it does, mobile devices are becoming more powerful and the energy savings per unit of work is absorbed by the greater complexity of devices. In this perspective, two new approaches can make a difference.

The first is related to the manner in which energy is dispatched within a chip and among modules that are co-located on a mobile device. Indeed while microelectronics becomes smaller and denser, and more energy efficient, the proportion of wasted energy due to leakage currents actually increases. All modules in a microelectronic system, or on a chip, are not simultaneously active yet they are typically always powered; leakage currents and energy losses can occur even when they are inactive. Multi-core systems achieve reduced energy consumption when certain cores are not utilized, and this could be generalized to system modules. Thus we will investigate the provision of energy “on demand” within components of a chip and modules, and analyze the resulting energy savings.

The second one, energy harvesting (EH), is a promising remedy to increase the lifetime of wireless devices by reducing their dependency on stored energy, by exploiting alternative energy sources. Devices with

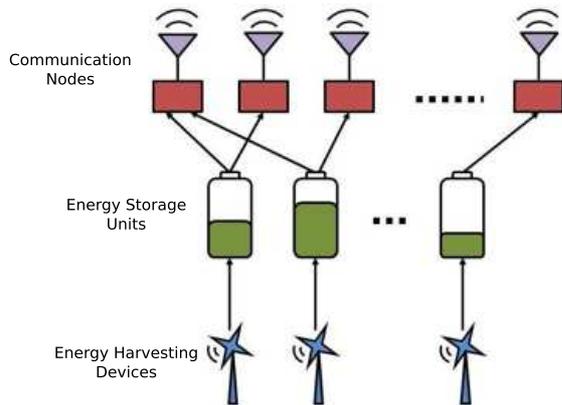


Fig. 2. A network of communication nodes, storage units and energy harvesting devices.

EH capability can scavenge ambient energy, such as vibrations, thermal gradients or solar energy, to power communication and computing while storing the excess energy in batteries or capacitors. Figure 1 shows an EH module that supports a temperature sensor.

Energy efficient communication schemes have been extensively studied for wireless networks [8]–[10] as well as wired networks [2], [16]. While most of the existing literature focuses on minimizing energy expenditure assuming that the communication devices are connected to the power infrastructure, or have an initial energy budget stored in batteries, EH techniques have the potential to provide perpetual energy for mobile network nodes, so that running out of energy is no longer a problem. However, in most cases the supply of harvested energy is not deterministic. Thus the stochastic behavior of energy supply calls for the design of new communication and networking techniques [11], [12]. Much effort has been spent to optimize either the communication protocols under constant power/energy resources or the energy utilization in networks of EH devices when the energy demand of the network nodes is known. However, a general mathematical framework combining both energy management and physical layer/networking design in a communication network context is still lacking. Moreover, essential properties of energy harvesting processes associated with different technologies (such as thermal and vibration-based, in addition to solar, which is currently the most common and well-studied) need to be better understood and modeled.

E-CROPS is a new CHIST-ERA project that was ranked first in the peer-reviewed European CHIST-ERA competition. It has started in February 2013 to study the design of networks of communication nodes (CN) with energy storage units (ES) that can be supplied from

EH devices. This challenge is of a cross-layer nature to jointly optimize the communication/ networking algorithms with the management of energy. Thus the goal of E-CROPS is to develop realistic models, and use them to obtain theoretical bounds as well as algorithms for the optimal operation of EH networks such as the one sketched in Figure 2.

Unlike most “green radio” research projects, E-CROPS does not simply focus on the design of more spectrally efficient communication systems and rephrase the benefits from a “green radio” perspective. The goal of E-CROPS is to introduce a new paradigm for energy efficient networking, to radically change the design assumptions on the nature of energy supplies (based on renewable energy sources) and to design novel communication and energy management protocols from scratch based on this new framework. As a result, the E-CROPS project will have three closely knit aspects:

- On the theoretical end, we will formulate a mathematical theory of network communications in the presence of EH and storage devices, which takes into account the behavior of energy generation, storage and utilization processes together with the properties of the communication network. For example, in a simple point-to-point setting, we need to optimize the scheduling of the transmission of data packets based on the energy arrival profile of the EH device at the transmitter; or, in the case of multiple sensor nodes, all supplied by the same EH device, we need to jointly optimize the utilization of the energy and the communication and networking protocols to transmit the sensor observations to the access point.
- Within a given hardware architecture, we will develop mathematical techniques based on queuing networks where “energy packets” are flowing, analyze the effects of harvesting and storage (in batteries and capacitors) together with their corresponding losses due to transport and conversion, and optimally identify the required harvesting-storage-conversion-consumption architectures to meet the communication needs.
- The other, more experimental and practical aspect of the project, will design vibration-based EH devices and storage units that support the operation of a sensor network.

In E-CROPS, the EH and storage unit design on the one hand, and the theoretical study on the other, will interact since the realistic EH profiles of the practical designs will provide parameters to the optimization algorithms, while the analysis and optimization methods

in turn will specify characteristics of the communication nodes (such as performance and energy needs) that will be used to design the EH and storage devices. As a proof-of-concept demonstration for E-CROPS, a novel vibration-based energy harvesting and storage system will be designed and implemented for a real wireless sensor network.

II. ENERGY PACKET NETWORKS

The concept of “energy packets” and the analogy between the flow of energy in the electric grid, and of the flow of data in the Internet, has been mentioned as early as 1997 [13]; recent work discussing the analogy between the smart grid and the Internet includes [14]. The concept of an Energy Packet Network (EPN) is different. It is inspired by work on queuing networks called G-networks [15] that include both the flow of a commodity, in our case energy represented by discrete energy packets (EP), and the flow control and storage of this commodity with the help of a controlling communication network [7], [14]. This approach allows the representation of choices regarding the distribution of the flows through the EPN via routing probabilities for EPs, and the routing probabilities can be modified to optimize the system’s performance. The EPN model also incorporates the delays and possible losses of the controlling data network.

The data flows are coupled to the decisions to transfer EPs towards the consuming modules, whose energy consumption is coupled with their computational service and is also represented by a stochastic service process. Thus in this model the EPs constitute the “ordinary customers” of the queuing network, both the energy storage units (ST) and the data packet buffers are modeled as queues, the external arrivals of EPs are the energy produced by different sources of energy, and the G-network’s “triggers” [7], [14] are the data flows regarding requests made by the hardware whose ST (batteries and capacitors) are emptied as computation progresses, and replenished through EH or other external energy sources. The EPN has a set of energy sources each with an energy generation rate $g(i, t)$ in EP/sec at time t where i refers to the source of energy, and $g(i, t) \leq GM(i)$ is its maximum generation rate. The energy sources are either renewable, in which case i is in R , or they are conventional, i in C . The system has a finite storage capacity $K(j)$ for the j -th ST. Each storage centre has an energy conversion efficiency $0 < e(j) < 1$ at its input so that on average the arrival of $B'(j)$ energy packets to this ST results in the storage of $B(j) = e(j)B'(j)$ EPs. Furthermore, in addition to its maximum energy storage capacity, it will also have a maximum rate at

which it can store energy, and an energy loss rate so that if storage is not replenished, the $B(j)$ EPs that it contains will be depleted after some time. In addition, an ST will deliver energy at some rate $d(j, t) < D(j)$, less than the maximum rate $D(j)$ at which it can deliver energy. The computing or communication modules (CM) are the main energy consumers. Some CMs may also store energy locally. The CMs are connected to an energy distribution network (EDN) so that link (u, v) models the power line with capacity $C(u, v)$ which is the maximum amount of energy transferred instantaneously from node u to node v ; its efficiency $0 < c(u, v) < 1$ is the fraction of energy entering the link that reaches the destination. The nodes of the EDN may be production nodes, CMs, or STs. Each CM requests energy from the Smart Dispatching Centre (SDC) which tracks the requests in an area and assigns flows from the STs and EGs to the CMs. The SDC also directs the EGs and EHs to fill the STs. We represent by the probability $q(u, v)$, the fraction of energy leaving node u which is directed towards node v , while $p(u, v) = q(u, v)c(u, v)$ is the probability that an EP leaving u actually arrives at node v . Furthermore, $Q(v, u)$ will be the probability that when node v consumes or dispatches energy to some other node, then it also requests energy from some other node u . EH will be represented by random flows while the time dependent energy consumption rate of CMs will be represented by random variables. A G-Network model [14] with stochastic representations of energy production, storage and consumption will represent the behavior of the EPN to jointly optimize effective computation and communication as a function of workload and energy availability of different types including EHs. Techniques based on various learning algorithms [17], [18] will also be used to study self-adaptive schemes that address this overall optimization.

III. SCHEDULING WITH STOCHASTIC ENERGY SUPPLY

In E-CROPS energy is the key resource that needs to be optimally utilized, while satisfying the communication requirements. This can be achieved by i) properly selecting the source of energy to be used (stored or instantaneously harvested), ii) moving energy around the network to prevent energy starvation and network outages, and iii) optimizing the communication protocols by making judicious choices for power assignment, rate allocation, scheduling, routing, etc. As mentioned in the Introduction, with microelectronic systems becoming smaller and less energy demanding, transmission energy becomes dominant in the energy usage of small

transceivers; hence, we focus first on the optimization of the transmission power over time.

Consider an additive white Gaussian noise channel $Y = X + Z$, where Z is the independent Gaussian noise component with zero mean and variance σ^2 . In the classical information theoretic approach, we assume a source with constant power limited to P , and derive the highest information rate (bits/second) from the Shannon bound in bits/sec: $\frac{1}{2} \log \left(1 + \frac{P}{\sigma^2} \right)$.

The channel capacity is achieved by sending infinitely many bits over infinitely many channel uses. However, the intrinsic assumption behind this formulation is that power P is available throughout the transmission, which leads to unbounded energy consumption. Hence, the classical information theoretic approach identifies the trade-off between the power and the rate for a system connected to a constant power energy source. However, if we are given a finite energy budget E , rather than a power constraint, which would be the case for a transmitter running on a finite battery, the problem changes significantly. The goal now is to transmit the highest number of bits before running out of energy. Assuming that transmission lasts T seconds, the optimization problem becomes:

$$\max \int_0^T \frac{1}{2} \log \left(1 + \frac{P}{\sigma^2} \right) dt \text{ s.t. } \int_0^T p(t) \leq E,$$

where $p(t)$ is the transmission power at time t . Using Jensen's inequality, we can see that the number of transmitted bits is maximized by transmission at constant power, i.e., $p(t) = E/T$ for all $t \in [0, T]$, resulting in the transmission of a total of

$$\frac{T}{2} \log \left(1 + \frac{E}{T\sigma^2} \right) \text{ bits}$$

in T seconds. This is maximized by letting T tend to infinity; hence, by transmitting with diminishing power over time. The maximum number of bits that can be transmitted is

$$\frac{E}{e^{2\sigma^2}}.$$

Note that this formulation focuses on the trade-off between the energy and the total number of bits that can be transmitted, while in practice data is encoded in finite length blocks, as amortizing an infinite number of bits over an infinite number of channel uses is not practical from a delay perspective. With a finite delay constraint, the energy per bit will be higher than the ideal zero-rate limit we have evaluated above, even for finite error probabilities. Therefore, the dimensions of the trade-off include energy, delay and number of bits.

In the case of an EH transmitter, depending on the type of energy source, energy arrival can be almost

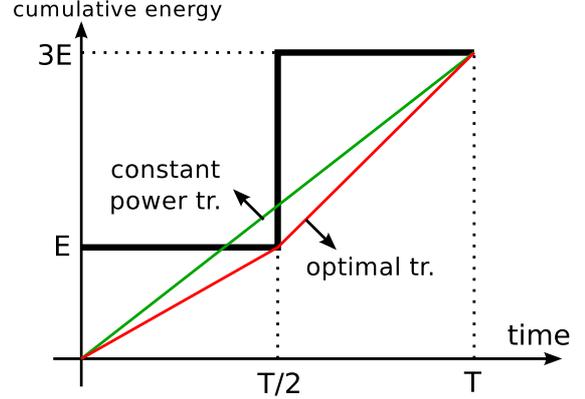


Fig. 3. Optimal scheduling with energy packet arrivals.

deterministic (e.g. vibrations on a railway), highly time-varying and somewhat random but predictable (e.g. solar energy) or, highly random and unpredictable (e.g. wind energy). Thus the optimal transmission scheme depends on the energy arrival process itself, and the knowledge available about the process. Assume that the energy arrival times and amounts are known a priori. We want to maximize the total number of bits that can be transmitted by the system until a deadline T for a given energy arrival profile. Let the initial available energy in the battery be E , while another energy packet of size $2E$ arrives at time $T/2$. We illustrate the available cumulative energy in Figure 3 with the solid black line. The rate relates to the transmission power through a concave function (for example, for the Shannon capacity). It follows from the concavity of the rate-power relation that the optimal transmission scheme keeps the transmit power as constant as possible, while using up all the energy by the deadline [19]. However, keeping the power constant throughout the whole transmission, illustrated as the green line in the figure, requires a total energy of $3E/2$ by time $T/2$. This contradicts the “energy causality principle”, which dictates that no energy can be used before it arrives at the battery. The optimal cumulative transmission energy is illustrated as the red curve in Figure 3: the optimal policy never idles, i.e., never stops transmitting until the deadline, and the optimal transmission power only increases. This problem gets more involved when data arrives over time rather than being available initially [19], battery capacity is limited and leaks [20], [21], the number of nodes in the system increases [22]–[26] or the processing energy is taken into account [27]; all of which will be investigated within the E-CROPS project. Moreover, in addition to optimal solutions, E-CROPS will also aim to obtain performance bounds that apply to networks of any size and

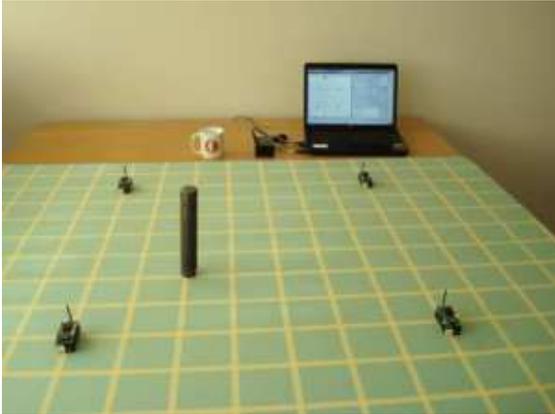


Fig. 4. Wireless sensor network application that will be integrated with the developed energy harvesting technology.

complexity. In addition to optimizing the transmission power policy for an improved rate performance from EH-constrained transmitters, we also consider the impact of the EH framework on feedback-aided wireless networks. Feedback of channel state information from a receiver to its serving transmitter can substantially improve the capacity performance of certain radio links, notably in multi-antenna-aided systems. Nevertheless, the allocation of resources towards feedback transmission can be costly and should be scheduled wisely. We argue that this is even more so when the terminal is subject to random energy packet arrivals. In [33] we show how an EH-constrained terminal should allocate its finite battery resources towards maximizing the ergodic rate by feeding back channel state information only when worth it. See [28] for a more detailed overview of the ongoing research efforts and potential future directions on EH communication networks.

IV. SYSTEM DEMONSTRATOR

For the demonstration part, we will use a wireless sensor network (WSN) of MicaZ motes equipped with MTS10CB sensor boards, that has been implemented primarily for ferromagnetic object localization and identification, at the METU Communication Networks research group [31] (see Figure 4). Leveraging the work of the METU MEMS group on the design of vibration-based energy harvesters [32], we will custom design and manufacture energy harvesters to use in place of or concurrently with batteries on the sensor nodes, such that some of the nodes will be supplied by the energy scavenged through vibrations. The scenario in mind for implementing this prototype is the detection of vehicles entering an area, where sensors will be located in the tar-

mac to maximize the harvested energy from the passing cars. The combination of the network prototype with harvesters will require optimizing network operations and node duty cycles carefully, as the power available from typical vibration frequencies is lower compared with the power use of the devices in their active state. The network will use the energy-efficient clustering based Heed protocol, in addition to the standard Collection Tree Protocol, running beneath the custom designed scheduling schemes to be developed within the project. We will compare the lifetimes of harvester-equipped and fixed-battery nodes running side by side. Challenges regarding the choice of appropriate storage units, the specifications of the harvesting unit to generate sufficient energy to drive the sensor nodes, making the harvesting, storage and sensing units compatible, determining the energy cost of the sensing and communication processes of the sensor node, will all be dealt with in the implementation part of the project. As vibration energy harvesting is relatively new in communication applications, we believe that the experimental results will be invaluable for the modeling aspects of the project.

V. CONCLUSIONS

Design of energy saving wireless networks is an important research area that can give a competitive edge to the once-dominant European telecommunications industry against its counterparts in the rest of the world. As the ICT sector increases its presence in our lives, it also becomes an important factor in the global energy consumption. With this trend, energy efficiency and sustainability becomes especially important for future generations of communication systems. E-CROPS will strive in this direction, and disseminate its results in the form of guidelines to help to pave the way for European industry to design the best possible Green ICT solutions. Research on EH systems is heavily funded in the US and Japan, and we believe that E-CROPS is a timely step forward so that Europe will not fall behind in this crucial area of research and development.

REFERENCES

- [1] V. Raghunathan, S. Ganeriwal, and M. Srivastava, "Emerging techniques for long lived wireless sensor networks," *IEEE Comms. Magazine*, 44 (4): 108-114, 2006.
- [2] E. Gelenbe and C. Morfopoulou, "A framework for energy aware routing in packet networks" *The Computer Journal*, (54) 6, 2011.
- [3] A. Jain, D. Gunduz, S. R. Kulkarni, H. V. Poor and S. Verdu, "Energy-distortion tradeoffs in Gaussian joint source-channel coding problems," *IEEE Trans. Information Theory*, vol. 58, no. 5, pp. 3153-3168, May 2012.

- [4] Gartner, Inc. "Gartner estimates ICT industry accounts for 2 percent of global CO2 emissions," www.gartner.com/it/page.jsp?id=503867, 2007.
- [5] A. Berl, E. Gelenbe, M. di Girolamo, G. Giuliani, H. de Meer, M.-Q. Dang and K. Pentikousis, "Energy-Efficient Cloud Computing", *The Computer Journal*, 53 (7), 2010.
- [6] E. Gelenbe and G. Loukas "A self-aware approach to denial of service defence", *Computer Networks*, 51 (5), 1299–1314, 2007.
- [7] E. Gelenbe, "Energy packet networks: Adaptive energy management in the cloud", *Proc. 2nd Intl Workshop on Cloud Computing Platforms*, NY, USA, 2012.
- [8] E. Uysal-Biyikoglu, B. Prabhakar, and A. E. Gamal, "Energy-efficient packet transmission over a wireless link," *IEEE/ACM Trans. Networking*, 10 (4): 487-499, 2002.
- [9] A. Goldsmith and S. B. Wicker, "Design challenges for energy-constrained ad hoc wireless networks," *IEEE Wireless Comm. Magazine*, vol. 9, no. 4, Aug. 2002.
- [10] E. Gelenbe "Search in unknown random environments", *Phys. Rev. E*, 82: 061112, 2010.
- [11] D. Niyato, E. Hossain, M. Rashid, and V. Bhargava, "Wireless sensor networks with energy harvesting technologies: A game-theoretic approach to optimal energy management," *IEEE Trans. Wireless Communications*, vol. 4, no. 4, pp. 90-96, Apr. 2007.
- [12] J. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics" *IEEE Perv. Comp.*, 4 (1):18-27, 2005.
- [13] J. Toyoda and H. Saitoh, "A proposal of an open-electric-energy-network (OEN) to realize cooperative operations of IOU and IPP", EMPD, Mar. 1998.
- [14] E. Gelenbe, "Energy packet networks: Modeling smart electricity storage to meet surges in demand", *5th International Conf. Sim. Tools and Techniques SIMUTOOLS*, March 2012.
- [15] E. Gelenbe, "The first decade of G-networks," *European J. of Operational Research*, 126 (2): 231-232, 2000.
- [16] E. Gelenbe, "Steps towards self-aware networks", *Communications ACM*, 52 (7): 66-75, July 2009.
- [17] P. Blasco, D. Gunduz, M. Dohler, "A learning theoretic approach to energy harvesting communication system optimization," *IEEE Trans. Wireless Communications*, vol. 12, no. 4, pp. 1872-1882, Apr. 2013.
- [18] P. Blasco, D. Gunduz, M. Dohler, "Low-complexity scheduling policies for energy harvesting communication networks," *IEEE Int'l Symposium on Information Theory (ISIT)*, Istanbul, Turkey, Jul. 2013.
- [19] J. Yang and S. Ulukus, "Optimal packet scheduling in an energy harvesting communication system", *IEEE Trans. on Communications*, 60 (1): 220-230, Jan. 2012.
- [20] B. Devillers and D. Gunduz, "A general framework for the optimization of energy harvesting communication systems with battery imperfections," *Journal of Comms. and Networks*, 2012.
- [21] K. Tutuncuoglu and A. Yener, "Optimum transmission policies for battery limited energy harvesting nodes," *IEEE Transactions on Wireless Communications*, vol. 11, no. 3, pp. 1180-1189, Mar. 2012.
- [22] D. Gunduz and B. Devillers, "Multi-hop communication with energy harvesting," *Proc. of CAMSAP*, San Juan, Puerto Rico, Dec. 2011.
- [23] O. Orhan and E. Erkip, "Optimal transmission policies for energy harvesting two-hop networks," in *Proc. Conference on Information Sciences and Systems*, Princeton, Mar. 2012.
- [24] M. A. Antepi, E. Uysal-Biyikoglu and H. Erkal, "Optimal packet scheduling on an energy harvesting broadcast link," *IEEE J. on S. Areas in Comm.*, 29 (8): 1712-1731, 2011.
- [25] J. Yang and S. Ulukus, "Optimal packet scheduling in a multiple access channel with energy harvesting transmitters," *Journal of Communications and Networks*, 14(2):140-150, Apr. 2012.
- [26] K. Tutuncuoglu and A. Yener, "Sum-rate optimal power policies for energy harvesting transmitters in an interference channel," *JCN Special Issue on Energy Harvesting in Wireless Networks*, vol. 14, no. 2, pp. 151161, Apr. 2012.
- [27] O. Orhan, D. Gunduz and E. Erkip, "Throughput maximization for an energy harvesting communication system with processing costs", *IEEE Information Theory Workshop (ITW)*, Lausanne, Switzerland, Sep. 2012.
- [28] D. Gunduz, K. Stamatiou, N. Michelusi and M. Zorzi, "Designing intelligent energy harvesting communication systems," revised, *IEEE Communications Magazine*, 2012.
- [29] S. Chalasani and J. M. Conrad, "A survey of energy harvesting sources for embedded systems," *IEEE Southeastcon*, 2008.
- [30] W.K.G. Seah, Z.A. Eu and H.P. Tan, "Wireless Sensor Networks Powered by Ambient Energy Harvesting – Survey and Challenges," *Proc. 1st Int. Conf. on Wireless Comms., Vehicular Tech., Inf. Theory and Aerospace and Electronic Systems Tech. (Wireless VITAE)*, May 2009, Aalborg, Denmark.
- [31] S. Baghaee, S. Z. Gurbuz and E. Uysal-Biyikoglu, "Application and modeling of a magnetic WSN for target localization", *IEEE UKSim2013, 15th International Conference on Modelling and Simulation*, 2013.
- [32] A. Rahimi, O. Zorlu, A. Muhtaroglu, and H. Kllah, "A fully self-powered electromagnetic energy harvesting system with highly efficient dual rail output", *IEEE Sensors Journal*, Vol. 12, No. 6, June 2012.
- [33] R. Gangula and D. Gesbert, "Optimizing feedback in energy-harvesting MISO communication channels", submitted to *IEEE GlobalSIP Conference*, Austin, TX, 2013.