2011 Eighth IEEE International Conference on Mobile Ad-Hoc and Sensor Systems

SWAP Project: Beyond the State of the Art on Harvested Energy-Powered Wireless Sensors Platform Design

Nicola Bui*, Apostolos Georgiadis†, Marco Miozzo†, Michele Rossi‡, Xavier Vilajosana§
†Centre Tecnològic de Telecomunicacions de Catalunya, Castelldefels, Barcelona Spain — {ageorgiadis,mmiozzo}@cttc.es
*Patavina Technologies S.r.l., Italy — nicola.bui@patavinatech.com
‡Consorzio Ferrara Ricerche, Ferrara, Italy — mrossi@ing.unife.it
§Worldsensing, Barcelona, Spain — xvilajosana@worldsensing.com

***Abstract*—The main goal of the SWAP project is that of designing, implementing and ultimately testing a new breed of wireless sensor nodes with energy scavenging capabilities. Our design will include novel energy scavenging hardware as well as network protocols and algorithms. In this paper, we summarize the outcomes of the first year of the project as well as the way forward to the further phases. In particular, we analyze the state of the art in the main research areas: energy efficient communication protocol design, ultra–low–power hardware design and most advanced harvesting techniques.**

For what concerns the future phases of the project we elaborate on the adoption of statistical predictive models for the energy description, we account for game theoretic approaches for distributed optimization and we apply our considerations on the most modern standards for wireless sensor networks communication. We review the state of the art on hardware components, to provide a shortlist of the most efficient building blocks of the SWAP platforms as well as a draft version of the schematics of the module. Finally, we provide a brief overview on the latest energy harvester for miniature scale devices and we argue on the feasibility of a hybrid solar–electromagnetic harvesting module.

I. INTRODUCTION

Symbiotic Wireless Autonomous Powered system (SWAP) combines the energy-efficient paradigm of wireless sensor networks with the self-sustainable capabilities of harvesting systems. SWAP aims at providing a novel sensor board consisting of *i)* a high efficiency RF transceiver, *ii)* a low power micro controller, *iii)* an energy accumulator and *iv)* modular harvesting systems. To this aim SWAP will study advanced solution for RF circuits and antennas, will use state of the art micro controllers, will implement highly efficient accumulator and will investigate on harvesting techniques. In particular, the different harvesting modules will be applied to standard sensor networks scenarios: for instance, environmental monitoring networks are more likely to use photo voltaic cells, while urban sensor networks can use instead vibrations, and harvest the available ambient electromagnetic (EM) energy.

SWAP will also study communication protocol from the physical to the network layer in order to implement the techniques offering the highest efficiency as well as taking into consideration the temporary availability of energy sources. Also, the SWAP system will be realized and tested on the field; applications will be developed in order to provide the basic services for the new platform. As a final result, SWAP aims at obtaining a new wireless sensor paradigm totally independent from batteries and having the least impact on the environment.

This paper describes the outcomes of the project after the first year of activity: during this period the main objectives of the consortium have been that of defining the application scenarios [1] for the proposed platform and that of collecting the latest state of the art. Moreover, this paper provides a roadmap for the next phases of the project.

The following sections provide an analysis of the state of the art by highlighting what is sufficiently advanced to be included in the SWAP platform, what needs further research and/or modifications and what is lacking and needs to be studied from scratch. In particular, Section II takes into account the latest advancements on protocols and algorithms design from both the industrial and academic sectors; Section III reviews the hardware market targeting, microcontrollers, RF transceiver and energy stage chips for ultra–low–power systems; Section IV leverages on the state of the art of harvesting solution and proposes a novel hybrid solar–electromagnetic harvester; Section V concludes the paper highlighting the way forward for the SWAP project.

II. PROTOCOLS AND ALGORITHMS

The first concrete output of the project SWAP has been the deliverable [2], which collected and reviewed the state of the art on energy harvesting techniques, sensor networks hardware solutions and communication suites developed by other European project (i.e.: GENESI [3]), the academic community and industrial organizations. On a popularity-based scale, the most prominent solution is the ZigBee communication protocol stack [4]. The open communication protocol stack consists of a combination of the efforts of IEEE and IETF; this solution

This work has been supported in part by the FP7 EU projects "SWAP" G.A. no. 251557

978-0-7695-4469-4/11 $26.00 © 2011 IEEE
DOI 10.1109/MASS.2011.97

IEEE computer society

includes 802.15.4 [5], 6LoWPAN [6], RPL [7] and, optionally, CoAP [8]. Open source implementers and computer science groups are adopting this standards-based solution and two realizations are already available: Blip [9] and uIPv6 [10], which are implemented for TinyOS and Contiki operating systems, respectively.

From a pure scientific perspective, many solutions have been proposed in the last years applying to different levels of the protocol stack. Concerning the MAC layer, the most promising solution is represented by duty-cycle schemes, where optimizing the sleep and wake-up strategies, it is possible to improve the performance from energy expenditure perspective for solar powered devices. In this case, Markov chains are used to model both the harvested energy availability and the energy accumulator, as done in [11].

Many routing solutions exist for optimizing the path according to a cost function: in [12] a distance vector paradigm is used which accounts for both the current availability and the prediction of the harvested energy. An alternative proposal is the geographical approach proposed in [13], where the route selection is performed considering the first-hop neighborhood positions and the energy levels.

Energy-driven scheduling solutions have been studied, such as in [14] where the capacity of the nodes energy storage and the power consumption has been coupled to the classical QoS dependent parameters in formulating the scheduling policy.

A further paper is [15] where the authors optimize routing in a multi-hop and distributed WSN, subject to 1) queue stability at all nodes, 2) self-sustainability of the network nodes in terms of energy resources, 3) a generic user-defined metric, which is used to drive the optimization.

Scalability and energy efficiency are key to sensor networks, and for this reason distributed solutions based on game theory have been proposed. In [16], the power consumption is minimized in a distributed fashion while ensuring that network connectivity is preserved. In cooperative game theory players may cooperate to form coalitions for common interests. For instance [17] applies this approach to minimize the power invested in locating nodes, [18] for cluster formation, and [19] to maximize sleep time of the nodes.

A. Design of control algorithms

Some of the fundamental assumption of previous designs in the literature must be refined for actual energy-harvesting networks. For instance, in previous analyses the harvested energy income is assumed to be independent across different time slots. This amounts to neglecting the time correlation of the renewable energy process. As a consequence, the optimal policies that are derived from this assumption behave properly when the environmental conditions are stationary, but fail to deal with the cases where the physical phenomenon that governs the renewable energy process incurs phase transitions.

Our suggestion is that of including the time correlation into the mathematical description of the energy process and obtaining optimal solutions in terms of activity scheduling at the sensor nodes. Our preliminary simulation results indicate that such a time correlation is of fundamental importance and that the policies that are optimal for stationary processes are largely suboptimal when the statistics of the battery recharge process exhibits time correlation. In terms of theoretical analysis, we are planning to exploit the decisional Markov theory, through an adequate representation of the energy source. Probably, stochastic dynamic programming will be used as the optimization tool for the calculation of optimal activity schedules within single sensor nodes. Different methods may be needed for the extension of the results to network of nodes.

B. Resource allocation

Resource allocation is a difficult problem in WSN, as centralized solutions are typically not feasible, even worse in energy harvesting systems. We will consider the application of distributed tools, such as game theory, to allocate resources to ensure that energy is spent on the most valuable information.

An interesting application is the estimation of a random field value, which can be applied to temperature, stress, road traffic and vehicle speed monitoring. According to models for the random field and energy availability, transmissions from different sensors may be scheduled in a distributed fashion. In stationary fields, this process must ideally lead to a self-organizing system, where the optimal scheduling policy is established.

Regarding the application of game theory, such a system may be modeled using several games, but a common aspect is that a partial information model must be adopted, since assuming having perfect information of all sensor parameters is not feasible. Another important aspect is that the decision rules taken at the sensors must be very simple, given their limited processing and memory capabilities.

C. Recommendations for standard protocols

Based on the outcomes of the theoretical analyses in the previous two points, we are planning to look at the most prominent solutions in terms of data gathering, routing and channel access and see how these can be modified to efficiently support nodes with energy harvesting capabilities. Our modifications will be thus tested in our experimental lab to assess their validity.

III. HARDWARE

Considerable research efforts have been recently directed towards low profile, low power, energy efficient and self-sustainable sensor networks aiming at harvesting ambient energy. One of the SWAP project outcomes will be a wireless sensor platform based on the state of the art microelectronic components available on the market. The sensor node design will be driven by power consumption constraints, with a particular care to the communication system since it usually presents the larger power consumption.

Also, since SWAP aims at being able to support different harvester, the power regulation stage on the sensor board will be carefully designed in order to include the proposed harvesting solutions and to maximize battery drain. Electronic

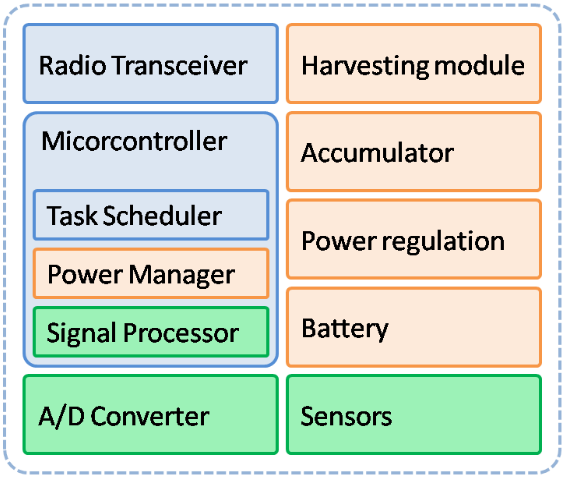

Fig. 1. The SWAP project wireless sensor platform is split in the represented components.

components will be chosen to be operational under a wide range of temperatures.

Fig. 1 present the block diagram of the SWAP platform as it is envisioned after the first year of the project. The main building block of the sensor node platform will be a state of the art microcontroller. Emphasis will be given to the power regulation stage, energy accumulator for harvesting means and the antenna design. Multiple expansion pins will be available to connect different sensor boards and devices. The state of the art collected in SWAP Deliverable D1.2 [2] allowed us to identify a selection of the most appropriate devices for each hardware building block. In the following subsections the different hardware components taken into account for the SWAP sensor platform will be presented.

A. *Power regulators*

In order to provide a very efficient power supply solution for sensor node and drain all the current available from a battery a switched power regulator will be used. System power drain during operation can go as high as 600 mA and is important to optimize the battery discharge down to 2.5 V or lower for long lifetime or when powered by harvested source.

To this end the TPS63030 [20] from TI, a switched power regulator will be used as the input DC/DC regulator for the sensor node. As we are dealing with ultra–low power device it is also very important that can be powered down to 1.8 V and that the device quiescent current is very small ($< 50\ \mu$A).

In order to more accurately regulate the power provided to the digital part of the board and to the radio device and avoid ripple effects from the switched DC-DC, two linear regulators from analog devices ADP163 [21] will be used. They are ultra–low quiescent current, low dropout, linear regulators that operate from 2.2 V to 5.5 V and provide up to 150 mA of very stabilized output current. Again current consumption in shutdown has been the main driver for selection.

Up to now, the energy harvesting power regulator stage of the sensor board has not been designed yet. A complete system for charging and protecting micropower-storage cells or any other battery source is envisioned. The desired IC needs to be able to manage poorly regulated sources such as energy-harvesting devices with output levels ranging from 1 W to 300 mW. Would also be desirable to have a boost regulator circuit for charging the batteries/cells from very low voltages. At the same time, the power regulation stage needs to output voltages for the digital or RF stages of the board, which can be done using an efficient adjustable low-dropout (LDO) linear regulator with selectable voltages of 3.3 V, 2.2 V, and 1.8 V.

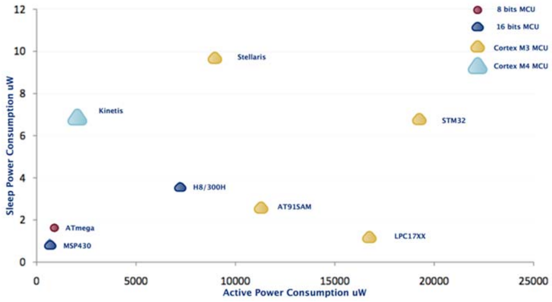

Fig. 2. Graphic comparisons of the most popular microcontrollers for sensor networks.

B. *Microcontrollers*

The most important features to take into account when choosing a microcontroller for the next generation of wireless sensor network applications are the computational power, the static and active power consumption, wake up times, operating voltage and working frequency.

To illustrate graphically the uC characteristics, Fig. 2 provides a classification of the different MCUs as a function of sleep power vs. active power and computational performance (marker size). As can be observed for 8 bits and 16 bits MCUs, they present lower power consumption at expenses of lower computational capabilities. Based on the previous evaluation processes and trying to achieve a good trade off between computation power and power consumption we determined that the most suited MCU for the SWAP sensor platform are:
i) Freescale Kinetis K60 [22] (32 bits): offers outstanding performance up to 100 MHz ARM Cortex-M4 core with DSP instructions delivering 1.25 Dhrystone MIPS per MHz, mounts up to 512 KB program flash memory allowing RTOS instructions and can be powered down to 1.71V.
ii) NXP LPC17XX [23] (Cortex M3): is an ARM Cortex-M3 based microcontroller for embedded applications requiring a high level of integration and low power dissipation. The LPC178x/7x is targeted to operate at up to 120 MHz CPU frequencies and equips up to 512 kB of flash program memory and up to 96 kB of SRAM data memory.Although the NXP LCP works at 2.5 V, thus increasing the power drain, its sleep power consumption is one of the lowest.
iii) MSP430 [24] (16 bits): is designed specifically for ultra-low-power applications. Despite it offers ultralow power consumption in both active and sleep mode, it presents limited computational power in front of the Cortex MX platforms. The MSP430 is based on proprietary architecture of 16 bits

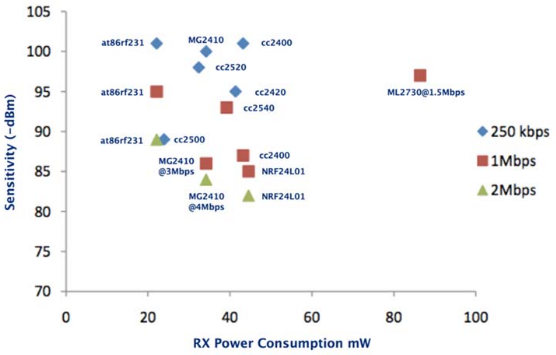

Fig. 3. Graphic comparisons of the most popular transceivers for sensor networks.

MCU limiting high demanding applications.

iv) ATMEL Atmega [25] (8 bits): is a high-performance, low-power 8-bit RISC-based microcontroller combines 128 kB ISP flash memory, 8 kB SRAM, 4 kB EEPROM. The device achieves a throughput of 8 MIPS at 16 MHz and operates between 2.7-5.5 V. Its low computational power and proprietary architecture are the main drawbacks against it.

C. Radio transceiver

Obtaining high bandwidth while minimizing the power consumption is becoming increasingly important. Low power communication strategies in wireless sensors include duty cycling radio operations, increasing data rates and improving devices RX sensitivity. Nowadays, the most widely adopted protocol for wireless sensor networks is IEEE 802.15.4 [5], and it exists a plethora of RF transceivers: for the SWAP platform the following chips have been selected: TI CC2520 [26], TI CC2420 [27], AT86RF231 [28] and MG2410 [29]. Radio sensitivity and power consumption were considered the most important features for component selection. Data rates and sensitivity at high data rates are important for new wave of WSN applications. In Fig. 3, radio Sensitivity vs. RX power consumption for each data rate of devices are presented. Both the AT86RF231 and the MG2410 offer very good trade off between power consumption and sensitivity at 2 Mbps or higher data rates. But we cannot discard CC2500 and CC2400 for their large market adoption, available platforms and development tools.

IV. HARVESTING TECHNIQUES

SWAP deliverable D1.2 State of the Art and Detailed Specifications [2], reported here in Table I, provides an indicative list of attainable harvested energy values, corresponding to solar, kinetic, thermal and electromagnetic harvesters based on existing products or published results in the literature. The indicated values are representative of the relative amounts of power that can be harvested by different energy harvesting technologies. In project SWAP the emphasis is placed on compact size, low cost harvester systems, such as the ones listed in Table I. Solar power appears as the largest and most commonly available source of ambient power. A challenge for third generation solar cells consists of increasing the power conversion efficiency while maintaining a low cost associated with materials and fabrication [30]. Kinetic energy harvesters are able to provide power levels in the order of mW and one important challenge associated with their utilization remains that of designing multi-band or frequency tunable harvesters [31]. Thermal energy harvesters also provide power in the order of mW and research in the field consists of optimizing the related devices and circuit topologies in order to increase the obtained conversion efficiency [32]. Electromagnetic energy harvesters provide the lowest harvested power, however they additionally allow for wireless power transmission, the capability to intentionally power a sensor device using a dedicated low cost transmitter [33]. Furthermore, the utilization of electromagnetic energy harvesters is supported by the fact that sensors typically operate in a wireless environment and scenario, which means that they require the use antennas and therefore the implementation of electromagnetic harvesters comes with a minimal cost.

TABLE I

INDICATIVE HARVESTED POWER FROM DIFFERENT TRANSDUCERS.

Energy Sources	**Harvested Power**	**Condition / Available Power**
Light / Solar	60 mW	6.3 cm x 3.8 cm Flexible solar cell AM1.5 Sunlight (100 mWcm^{-2})
Kinetic / Mechanical	8.4 mW	Piezoelectric shoe mounted
Thermal	0.52 mW	TEG ($\Delta T = 5.6$ K)
Electromagnetic	0.0015 mW	Ambient power density 0.15 uWcm^{-2}

The aforementioned challenges and indicative results of Table I point towards the necessity to implement hybrid energy harvesting systems combining two or more harvesting technologies, in order to increase the number of available energy sources for harvesting and thus maximize the amount of harvested power [33]. An additional challenge becomes that of maintaining a compact size of the sensors. Furthermore, the requirement for installation of a large number of sensors in different environments, such as for example body area networks, indoor room settings as well as outdoor agricultural settings, unavoidably leads to the necessity for conformal and flexible systems, both from an aesthetic point of view as well as due to space and size limitations. As a result, flexible materials such as PET, paper or textiles become attractive candidate materials for smart system implementations.

The proposed work in SWAP related to energy harvesting technologies focuses on the design of solar and electromagnetic energy harvesters and optimization of the harvesting circuit power conversion efficiency. An additional motivation behind the selection of these technologies comes from the fact that by careful design, it is possible to share the allocated circuit space between solar cells or modules and electromagnetic energy harvesting rectennas, thus maintaining a compact circuit layout. This concept was originally proposed in [34] for sharing communication antennas and solar panels in micro-satellites and the possibility of additionally utilizing electromagnetic energy harvesting rectennas provides an additional alternative architecture and perspective for hybrid harvesting circuit implementation. Furthermore, the combined use of flexible substrate materials for the rectenna circuitry and flexible solar cells for low cost, conformal architectures will be explored. The proposed work additionally includes circuit simulation and optimization techniques to maximize the conversion efficiency, which require the use of electromagnetic, nonlinear and linear circuit simulation techniques.

A. *Integration of solar cells with passive and active circuits*

The main task consists of demonstrating the integration of solar cells with antennas on a single substrate. Flexible solar cells will be used due to their low cost and conformal capability. Different substrate materials will be considered, while placing an emphasis on flexible materials.

Arlon A25N will be typically used for rigid substrate designs and polyethylene terephthalate (PET) will be typically used for flexible designs. Both materials have similar dielectric permittivity which simplifies the design process, although the available substrate thickness is different for the two materials. PET allows for conformal circuit implementations although it has higher losses compared to A25N.

The work includes the design of antennas integrated with solar cells, and different antenna prototypes and challenges will be considered, including narrowband patch or slot antennas as well as broadband monopole antennas in microstrip or coplanar waveguide technology. The antenna layout will be optimized using electromagnetic simulation in order to maintain the required input matching, radiation pattern characteristics and radiation efficiency when integrated with the solar cell.

B. *Optimized Rectifier Design*

This task includes the design of a broadband or multiband rectifier with optimized RF-to-DC conversion efficiency carefully taking into account the antenna characteristics and providing the maximum possible voltage and power to the subsequent sensor or energy storage circuit. Harmonic balance and envelope transient simulation combined with electromagnetic simulation tools will be used in order to design electromagnetic energy harvesting circuits with optimum efficiency.

The design tasks include the selection of the optimum rectifier circuit topology aiming at maximizing the conversion efficiency. Different rectifier topologies inspired from the power electronics community will be considered such as charge pumps with multiple diodes (e.g. Villard multiplier) and half-wave and full-wave rectifiers, and their efficiency will be computed and optimized.

C. *Hybrid Solar-Electromagnetic Energy Harvester*

Having successfully implemented the integration of solar cells with antenna elements as well as developed tools and prototypes of electromagnetic energy harvesters (rectennas), the design of solar-electromagnetic energy harvesters will be implemented. The design procedure requires the joint application of electromagnetic simulation as well as linear and nonlinear circuit simulation and optimization techniques. A working prototype of a solar rectenna on flexible substrates will be demonstrated. Characterization of the rectenna performance in terms of efficiency as well as bending conditions for the flexible implementations will be provided in the presence of the solar cell(s).

D. *Energy Storage Interface Circuit Design*

Finally, investigation of suitable interface circuits, such as DC-DC converters, necessary to provide a suitable voltage level from the output of the rectifier, to charge an energy storage element such as a super-capacitor or rechargeable battery will be considered. The task consists of studying DC-DC converter topologies from power electronic principles, with an aim to minimize the dissipated power associated with the DC-DC conversion circuitry and therefore maximizing the overall harvester efficiency. The work consists of efficiently simulating the complete chain from the RF/microwave input in the case of the electromagnetic harvester or the solar cell input to the DC output of the DC-DC converter circuit.

Architectures based on circuit topologies from the power electronics discipline will be considered such as a switched DC-DC boost or flyback converter, with an objective to minimize the dissipated power of the converter and efficiently charge the energy storage element. Printed circuit board (PCB) prototypes of the interface circuit will be fabricated and tested. Measurements include the interface circuit prototype efficiency and output voltage.

V. CONCLUSIONS

In this paper we provided a summary of the outcomes of the first year of the SWAP project: in particular we examined the state of the art on *i)* energy efficient protocols and algorithms design for wireless sensors networks, *ii)* ultra–low–power hardware components and *iii)* harvesting techniques.

In the next three years, SWAP will move first to the *Investigation & Design* phase (WP2), then to the *Validation & Integration* phase (WP3) and, finally to the *Implementation* phase (WP4). This paper, starting from the evaluation of the state of the art, describes the approach for the next phases.

At first, we are planning to come up with a mathematical model of the single sensor system, where we will adequately describe the energy source in terms of time correlation. This mathematical model will be subsequently used by a stochastic optimization algorithm,which will return the optimal scheduling of the nodes activities as its output. Optimal policies will thus be used within an accurate system simulator to pinpoint their benefits when compared with state of the art designs.

Also, the problem of optimally allocating the network energy to the most useful transmissions will be tackled using distributed algorithms based on game theory. We will deal with partial information, as well as with time variation of the harvesting process or the random field.

SWAP aims at combining these advanced research techniques with the most popular standards for the Internet of Things communication, in order to obtain a platform that, not only is able to achieve an unparalleled lifetime, but also will be seamlessly integrated with the Internet world.

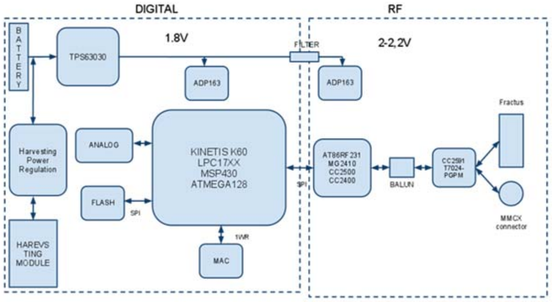

Fig. 4. The SWAP project wireless sensor platform hardware components.

Following the selection performed in Section III, Fig. 4 shows a first candidate of the block diagram of the SWAP sensor board. The diagram still provides multiple selection for the main components and it does not include the harvesting power regulation stage and the harvester modules, since these parts will be subject to a thorough evaluation phase in the next steps of the project.

Finally, to achieve the objectives presented in Section IV, the project will study *i)* the integration of solar cells and antennas on flexible substrates and will demonstrate their capability of operating an autonomous beacon; *ii)* flexible conformal electromagnetic harvesting circuit implementations using low cost substrate materials and off-the-shelf circuit components; *iii)* the design and implementation of hybrid solar electromagnetic energy harvesters and *iv)* a low power DC-DC converter circuits using off-the-shelf components.

REFERENCES

[1] "D1.1 Scenario and use cases," SWAP Deliverable. [Online]. Available: http://www.fp7-swap.eu/images/Documents/Deliverables/SWAP_deliverable_D1.1_final.pdf

[2] "D1.2 State of the Art and detailed specifications," SWAP Deliverable. [Online]. Available: www.fp7-swap.eu/

[3] "Green sEnsor NEtworks for Structural monitoring," Co-financed by the EC FP7. [Online]. Available: http://genesi.di.uniroma1.it/

[4] "Smart Energy profile 2.0," ZigBee alliance. [Online]. Available: www.ZigBee.org/Products/CertifiedProducts/ZigBeeSmartEnergy.aspx

[5] "IEEE 802.15.4 Standard Specification," downloadable at standards.ieee.org/getieee802/, 2006. [Online]. Available: {http://www.ieee802.org/15/pub/TG4.html}

[6] G. Montenegro, N. Kushalnagar, J. Hui, and D. Culler, "Transmission of IPv6 Packets over IEEE 802.15.4 Networks," IETF Request For Comments, Sep. 2007.

[7] T. Winter, P. Thubert, A. Brandt, T. Clausen, J. Hui, R. Kelsey, P. Levis, K. Pister, R. Struik, and J. Vasseur, "RPL: IPv6 Routing Protocol for Low power and Lossy Networks," IETF Internet Draft draft-ietf-roll-rpl-12, 2010. [Online]. Available: https://datatracker.ietf.org/doc/draft-ietf-roll-rpl/

[8] Z. Shelby, B. Frank, and D. Sturek, "Constrained Application Protocol (CoAP)," IETF Internet Draft draft-ietf-core-coap-06, 2010. [Online]. Available: http://datatracker.ietf.org/doc/draft-ietf-core-coap/

[9] B. WEBS, "BLIP 2.0 Berkeley IP." [Online]. Available: http://smote.cs.berkeley.edu:8000/tracenv/wiki/blip

[10] A. Dunkels, "Contiki uIPv6 6LoWPAN stack." [Online]. Available: http://www.sics.se/contiki/contiki-6lowpan-uipv6-faq.html

[11] D. Niyato, E. Hossain, and A. Fallahi, "Sleep and Wakeup Strategies in Solar-Powered Wireless Sensor/Mesh Networks: Performance Analysis and Optimization," *IEEE Trans. on Mobile Computing*, vol. 6, no. 2, Feb. 2007.

[12] Longbi Lin and Ness B. Shroff and R. Srikant, "Asymptotically optimal energy-aware routing for multihop wireless networks with renewable energy sources," *IEEE Trans. on Networking*, vol. 15, no. 5, pp. 1021–1034, Oct. 2007.

[13] Kai Zeng, KuiRen, Wenjing Lou, and Patrick J. Moran, "Energy aware efficient geographic routing in lossy wireless sensor networks with environmental energy supply," *Wireless Networks*, vol. 15, no. 1, pp. 39–51, Jan. 2009.

[14] Clemens Moser and Davide Brunelli and Lothar Thiele and Luca Benini, "Real-time scheduling for energy harvesting sensor nodes," *Real-Time Systems*, vol. 37, no. 3, pp. 233–260, Dec. 2007.

[15] L. Huang and M. J. Neely, "Utility Optimal Scheduling in Energy Harvesting Networks," in *ACM MobiHoc*, Paris, France, May 2011.

[16] Hongliang Ren and M.Q.-H. Meng, "Game-Theoretic Modeling of Joint Topology Control and Power Scheduling for Wireless Heterogeneous Sensor Networks," *IEEE Transactions on Automation Science and Engineering*, vol. 6, no. 4, pp. 610–625, Oct. 2009.

[17] O.N. Gharehshiran and V. Krishnamurthy, "Coalition Formation for Bearings-Only Localization in Sensor NetworksA Cooperative Game Approach," *IEEE Transactions on Signal Processing*, vol. 58, no. 8, pp. 4322–4338, Aug. 2010.

[18] H. Jing and H. Aida, "A cooperative game theoretic approach to clustering algorithms for wireless sensor networks," in *Communications, Computers and Signal Processing, IEEE Pacific Rim Conference on*, Victoria, B.C., Canada, Aug. 2009.

[19] O.N. Gharehshiran and V. Krishnamurthy, "Dynamic coalition formation for efficient sleep time allocation in wireless sensor networks using cooperative game theory," in *Information Fusion, 12th International Conference on*, Seattle, WA, U.S., Jul. 2009.

[20] Texas Instruments, "TPS63030: High Efficient Single Inductor Buck-Boost Converter with 1-A Switches." [Online]. Available: http://focus.ti.com/docs/prod/folders/print/tps63030.html

[21] Analog Devices, "ADP163: Ultralow Quiescent Current, 150 mA, CMOS Linear Regulators." [Online]. Available: http://www.analog.com/en/power-management/linear-regulators/adp163/products/product.html

[22] Freescale Kinetis, "K60: Low-Power MCU with optional Floating Point Unit, Ethernet, USB, Encryption and Tamper Detect." [Online]. Available: http://www.freescale.com/webapp/sps/site/prod_summary.jsp?code=K60

[23] NXP Semiconductiors, "LPC17xx microcontroller series." [Online]. Available: http://ics.nxp.com/products/lpc1000/lpc17xx/

[24] Texas Instruments, "16-Bit Ultra-Low Power MSP430 Microcontrollers." [Online]. Available: http://focus.ti.com/docs/prod/folders/print/msp430f2616.html

[25] ATMEL Corporation, "ATMega128: 8-bit AVR RISC-based microcontroller." [Online]. Available: http://atmel.com/dyn/products/product_card.asp?part_id=2018

[26] Texas Instruments, "CC2500: Low Cost, Low-Power 2.4 GHz RF Transceiver." [Online]. Available: http://focus.ti.com/docs/prod/folders/print/cc2500.html

[27] ——, "CC2400: Low-Cost and Low-Power Single-Chip 2.4 GHz." [Online]. Available: http://focus.ti.com/docs/prod/folders/print/cc2400.html

[28] ATMEL Corporation, "AT86RF231: Low Power RF at 2.4 GHz." [Online]. Available: http://atmel.com/dyn/products/product_card.asp?part_id=4338

[29] Radiopulse, "MANGO(MG2410): High Data Rate and Low Power 2.4 GHz RF Transceiver." [Online]. Available: http://www.radiopulse.co.kr/eng/main.html?mode=02_05

[30] M. Green, *Third Generation Photovoltaics, Advanced Solar Energy Conversion*. Springer, 2006.

[31] S. Roundy, "On the Effectiveness of Vibration-based Energy Harvesting," *Journal of Intelligent Material Systems and Structures*, vol. 16, no. 10, pp. 809–823, Oct. 2005.

[32] S. Beeby and N. White, *Energy Harvesting for Autonomous Systems*. Norwood: Artech House, 2010.

[33] A. Upson, "Putting Wireless to Work," *IEEE Spectrum*, p. 63, Jun. 2008.

[34] M. Tanaka, R. Suzuki, Y. Suzuki and K. Araki, "Microstrip antenna with solar cells for microsatellites," *Proc. 1994 IEEE International Symposium on Antennas and Propagation (AP-S)*, vol. 2, pp. 786–789, Jun. 1994.