An Overview on State-of-art Energy Harvesting Techniques and Choice Criteria: a WSN Node for Goods Transport and Storage Powered by a Smart Solar- based EH System

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Abstract- This paper describes a solar-based harvesting system able to properly power supply the sensor node of a Wireless Sensor Network (WSN) developed for ensuring traceability and services relatively to goods stored in containers placed in the monitored areas (e.g commercial seaport). Battery life-time is a main problem especially in networks where sensor nodes are not easily accessible. For this reason, sensor nodes are equipped with power management devices able to supply power, in an intelligent way, from the harvester when harvestable energy is available or from backup batteries, ensuring, under every operating conditions, the correct functioning of node. In this research work, an overview of the available energy harvesting technologies, showing some related devices present on the market, is presented; subsequently, the suitable energy harvesting technique for power supply the designed WSN node was chosen. Hence the smart node able to monitor the physical parameters deemed of interest related to stored goods and a solar-based harvesting board, based on LTC3330 IC, were designed and tested. Supercapacitors are charged when harvestable energy is higher than the one required from node; stored energy is then used in time periods with no harvestable energy before requiring the backup battery intervention.

Keywords- Wireless sensor network, solar cells, energy harvesting, harvester characterization, measurements, PCB.

1. Introduction

WSNs trend imposes a decrease of dimensions and power consumptions of sensor nodes and, at the same time, a WSN requirement is that the life-cycle and battery life of the sensor node and of the entire networks should increase. One possible solution to the sensor node's power supply that allows to increase battery life is the development of harvesting solution able to exploit the harvestable energies present in the environment where the sensor nodes are employed to work. There are lots of harvesting techniques to derive energy from the environment: the most common energy sources are mechanical, thermal, solar, chemical and electromagnetic [1-27]. Reference [1], for example, reviews the recent advances on various wind power harvesting techniques focusing on the miniaturized windmills or wind turbines which can generate a significant amount of power. Besides the windmills and turbines, summaries of various devices based on vortex-induced vibration, galloping, flutter, wake galloping, turbulence-induced vibrations, and other types reviewed are presented by the authors.

Reference [2] demonstrates the significant benefits of exploiting highly aligned porosity in piezoelectric and pyroelectric materials for improved energy harvesting performance; the authors constructed a pyroelectric energy harvesting device and demonstrated that the fastest charging speed and maximum energy density were obtained when utilizing the highest porosity of 60 vol% for a parallel connected porous lead zirconate ceramic. Therefore, the results of this research work, are beneficial for the design and manufacture of high performance porous pyroelectric and piezoelectric materials in devices for energy harvesting and sensor applications.

For feeding a WSN which operates under low vibrational conditions, a combined power extraction with an adaptive power management module for increased piezoelectric energy harvesting has been presented for the first time in [3]. The combined power extraction circuit and adaptive power management module allow to harvest up to 156 % more power from the strain energy harvester.

Reference [4] proposes an intelligent energy controller to manage operation of wireless sensor nodes equipped with energy harvesting devices; they, by simulating a wireless sensor network using real field-collected environmental data, focused their work on the optimization of the solar energy consumption, available for harvest, by preserving, at the same time, a backup energy reserve.

Anyway, the choice of the suitable energy source (or sources) to be used in the designed system, between all the possible available energy sources, is function of harvestable energy availability, of the application context and sensor node required power [5, 6].

In order to choose the suitable method for feeding properly the designed smart node (called *Medimote* ®), in this research work, the main energy harvesting techniques are investigated and analyzed in detail, making a comparison between them and presenting the technological trend that promises, more and more, advanced performances. Furthermore, for each discussed energy harvesting technique, some devices available on the market are shown and recent research works, which aim to increase devices performances in the energy harvesting field, are reported.

After the analysis of the possible energy harvesting techniques to employ for power supplying the sensor node, the solar energy was chosen taking into account the energy required by the WSN node and the environment in which the WSN will operate. Therefore, a smart electronic board based on LTC3330 IC, for energy harvesting and power management, has been designed able to ensure power supply of WSN node and optimal exploitation of available solar energy. In fact, the developed board allows to control and track the Maximum Power Point (MPP) of used small-size solar cells connected as input, by exploiting the LTC3330 functionalities. The proper functioning of sensor node and respective capabilities within the network are guaranteed under any condition of energy harvestable from the environment. To obtain this goal, the LTC3330 internal prioritizer carries out a control on availability of harvestable solar energy and involves backup battery to ensure proper operation of the sensor node, ensuring always a stable 3V DC supply output voltage for feeding the WSN node, only when harvesting source is not available and also super-capacitors are discharged [7-10]. Finally, experimental results showed a super-capacitor voltage drop, for each cycle, mainly due to WSN node transmission phase of detected parameters by using the Xbee transmission module.

2. Energy Harvesting Solutions: an Overview on the Available Technologies

Energy harvesting is the capture and conversion of small amounts of readily available energy in the environment into usable electrical energy that can be either directly used or accumulated and stored for later use. In literature, there are numerous basic articles on harvesting techniques that we have analyzed to provide a critical overview on available harvesting devices and systems [5-28]. The Table 1 reports a comparison in terms of obtainable output power for the various technologies of harvesting [5-17].

Table 1. Comparison of the available output powers from different energy harvesting technologies.

Harvesting Method	*Power density*
SOLAR	
Solar energy - outdoors	15mW/cm^3- bright sunny day 0.15mW/cm^3 - cloudy day
Solar energy - indoors	10 – 100 µW/cm^2
MECHANIC (Vibrations)	
Piezoelectric - shoe inserts	330µW
Electrostatic conversion	0.021µW/mm^3 - 105Hz
Electromagnetic conversion	184µW/cm^3
THERMIC	
Thermoelectric -5°C gradient	40µW/cm^3
PYROELECTRIC	
Temperature rate of 8.5°C/s	8.64 µW/cm^2
MAGNETIC	
Magnetic field energy	130µW/cm^3 - 200µT, 60Hz
RADIO FREQUENCY	
GSM 900/1800 MHz	0.1µW/cm^2
WiFi 2.4 GHz	0.01µW/cm^2
WIND	380µW/cm^3 (at the speed of 5 m/s)
ACOUSTIC NOISE	0.96µW/cm^3 at 100 dB 0.003 µW/cm^3 at 75 dB

Most energy harvesting applications are designed to be self-sustaining, cost-effective and to require little or no servicing for many years. In addition, the extracted power is used closest to the source, hence eliminating transmission losses and long cables. If the energy is enough to feed the device directly, the application or device powered by the energy can operate battery-less. The process of energy harvesting takes different forms based on the source, amount, and type of energy being converted to electrical energy [29-32]. In Fig. 1, a block scheme of an energy harvesting system, utilizing as power source the solar, vibrations, thermic, electromagnetic or other typologies of harvestable energy, is shown.

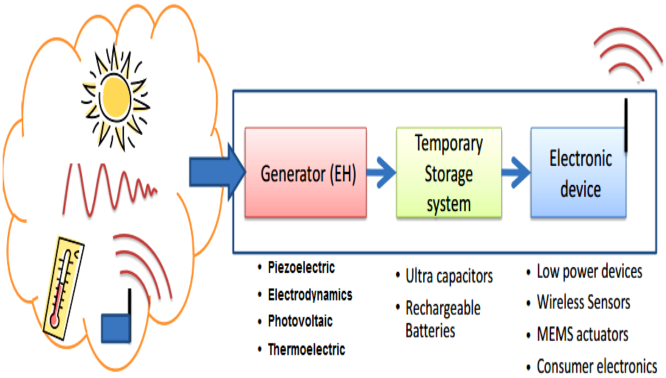


Fig. 1. Basic components and different energy sources of an energy harvesting system.

Before choosing the suitable energy harvesting technique for properly supplying the designed sensor node, some of the main forms of energy harvesting are described and analyzed in detail below.

2.1 Photovoltaic power generation for energy harvesting systems

One of the most common sources of available energy in nature is the solar energy; it is absolutely clean and non polluting. As shown in Table 1, solar energy allows to have more power when compared to other types of harvester, so it is used for feeding sensor nodes that consume lot of power. In a photovoltaic system, solar cells are used to convert sunlight into electrical power directly according to the photovoltaic principle. The photovoltaic effect refers to photons of light exciting electrons into a higher state of energy, allowing them to act as charge carriers for the generated electric current. Outdoor efficiencies range from 5% up to 20% according to the used materials; in indoor applications, the situation is much different since the illumination levels are much lower than outdoor. However, solar cells are used in numerous contexts and can provide significant power even using small modules; the possible implementation of harvesting systems based on solar cells is mainly linked to the scenario to be addressed. Tests that can be performed on solar cells are numerous, among which the most used to characterize their behavior are the quantum efficiency testing and current-voltage characteristic; this two kind of tests allow to obtain the spectral response of solar cells and the true value of photocurrent, namely the short-circuit current [8]. Due to the variability of the output power of the solar cells, that changes greatly as function of sunshine intensity and ambient temperature, proper circuits for the control or tracking of the maximum power point (MPP) are often associated with this type of harvester. MPP Tracking (MPPT) devices are able to constantly follow the MPP that a source is capable of delivering at a given instant, depending on the conditions to which the source is subjected [8]. MPPT or MPP Control devices are crucial when the powers to manage are extremely low, as in the case of harvesters [33-36]. Figure 2 shows the general block diagram of a solar cells-based harvesting system for wireless sensor networks.

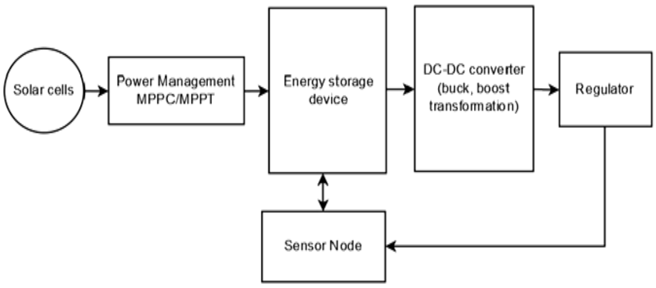


Fig. 2. Block diagram of solar energy harvesting system for low power application and wireless sensor nodes.

Therefore, the power management block is able to control and track the maximum power point of solar cells for providing to the load a constant supply voltage, even if the irradiation level strongly varies during the day. Solar cells are often used as an harvester for wireless sensor networks especially when the sensor node requires very high power; they are good candidates for feeding the WSN node thanks to their ability to capture environmental (solar) energy without the need of other particular conditions such as movements (vibrations), presence of electromagnetic fields or thermal changes that, on the contrary, are needed if other energy harvesting techniques are used. Obtained energy is stored in some rechargeable batteries or supercapacitors to be used at instants of time when there is not power availability from the harvester. In case of total absence of harvestable energy as well as from supercapacitors, sensor node can be powered using back-up battery thus ensuring always the normal device operation.

In conclusion, nanotechnology has shown promising developments in the field of renewable energy; relatively to the solar energy, new materials and technologies are used in the fabrication process of new solar panels [18-20]. Just for example, the Fig. 3 reports some last generation solar panels, available on the market, that present high performances and small dimensions.

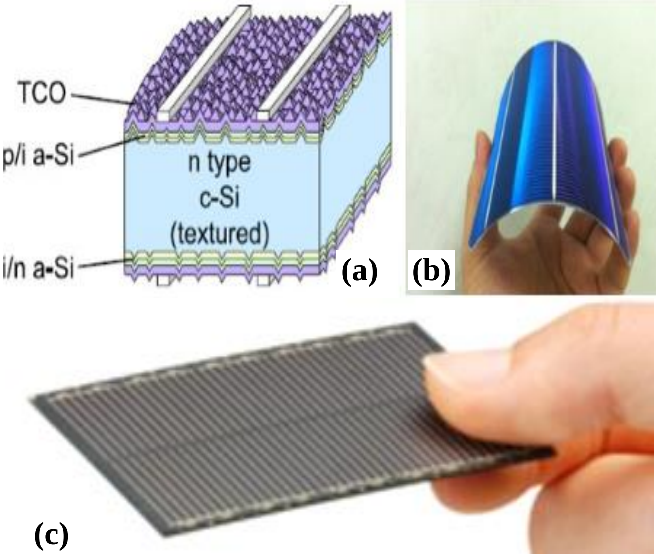
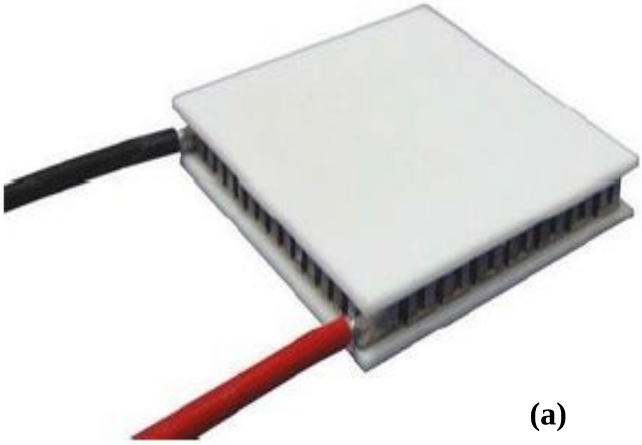


Fig. 3. Internal structure (a) and view (b) of a high-efficiency and flexible silicon-based solar cell produced by SITRI (Shanghai Industrial μTechnology Research Institute) and the LR0GC02 solar module for mobile devices produced by Sharp (c).

2.2 Thermoelectric power generation for energy harvesting systems

An energy source extremely helpful in nature is the thermal heat; in fact, the temperature difference between two ends of a semiconductor PN junction is used to generate electric power by a Thermoelectric Generation System (TEG) [21]. The thermoelectric devices utilize two different physical principles to convert heat into electricity: *Seebeck* and *Peltier* effects. The Seebeck effect is a classic example of an electromotive force (EMF) and leads to measurable currents or voltages in the same way as any other EMF. The heat flows from hot side to the cold side and, in the same way, free charge carriers in the material are also driven to the cold end. The heat flow will be present until the thermal equilibrium has reached and can be exploited to collect reusable energy; the resulting voltage (V) is proportional to the temperature difference (ΔT) via α (Seebeck coefficient). By connecting electron conducting (n-type) and hole conducting (p-type) materials in series, a proper voltage, that can be driven through a load, is produced. The process of extracting energy from the heat transfer is governed by the thermodynamic laws. The process efficiency is determined by the limit of Carnot and consequently by the temperature difference between the two surfaces of the thermo-electric generator. The *Peltier* effect is the presence of heating or cooling at an electrified junction of two different conductors and can be deemed as the opposite effect of the Seebeck one. However, the devices commercially available work with efficiency values much lower than the ideal efficiency and it is often necessary to have instantaneously very high temperature differences between the two surfaces to be able to store small amounts of energy [22]. Due to the low efficiencies and consequently low harvestable power, the use of these harvesters is limited to IoT devices or WSN nodes that require small amount of power for their functioning. For this reason and because of the absence of high temperature differences in the application context of the designed and implemented WSN, this energy harvesting solution, as discussed later, was not chosen. Figure 4 shows a thermoelectric generator commercially available and certain physical characteristics of the device.



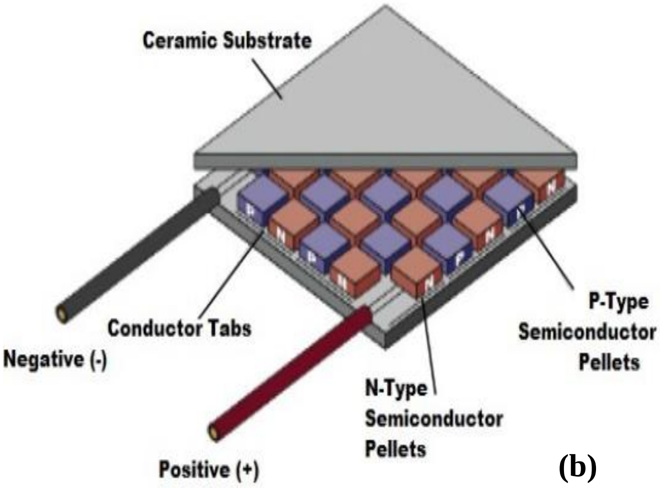


Fig. 4. Thermoelectric Generator Module: an example available on the market (a), physical characteristics and composition (b).

A TEG is composed of a series of n-type and p type thermoelectric semiconductors that are connected electrically in series and thermally in parallel. TEGs have recently attracted considerable interest for the generation of energy in low-power applications and for feeding electronic devices in the automotive field. Compared to other kind of harvesters, TEGs have lower efficiency but, for small applications, thermoelectric devices can become competitive because they are compact and scalable. Various thin film techniques have been utilized to produce small thermoelectric devices and advanced fabrication methods as well as Micro and Nano Electro-Mechanical Systems (M-NEMS), CVD and sputtering. More than 500 miniaturized thermoelectric generators in standard manufacturing range are available; TEGs are divided in several classes as function of dimensions, assembly technology, pellets density and performances. For example, a leader company in the fabrication of TEGs devices (*RMT Thermoelectric Cooling Solutions*), has realized several typologies; in Fig. 5, some of these devices are reported highlighting the dimensions and the reached integration level.

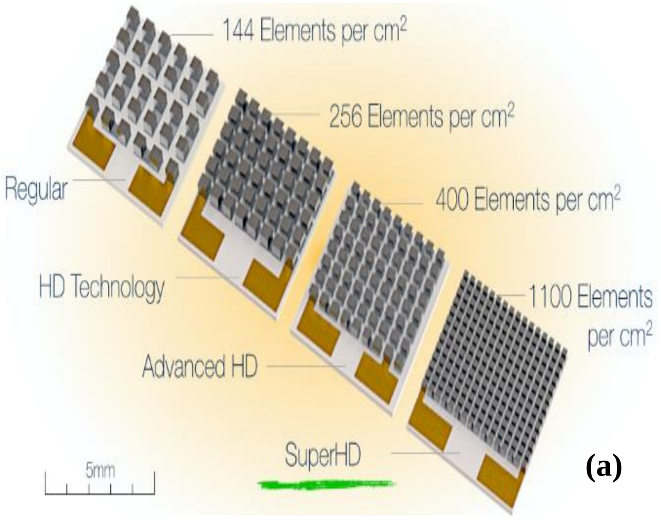


Fig. 5. TEGs devices provided by a company leader in thermoelectric generators fabrication: high density (HD) reached by the available technology (a) and photos of devices with indication of their dimension (b).

2.3 Piezoelectric-based devices for mechanical energy harvesting.

Another type of energy harvesting source comes from the mechanical energy; mechanical vibrations can be exploited through proper devices capable of converting the mechanical motion into electrical energy. The sources of mechanical energy can be a vibrating structure, a moving object or a vibration induced by flowing air or water. Mechanical energy, otherwise lost and unexploited, can usually be harvested by using vibration to electricity conversion [23]. Typically, circuital solutions able to perform this type of conversion are used to provide power to low-power electronic devices. The devices capable of converting the mechanical movement into electrical energy can be classified according to the principle of conversion used. The used principles are essentially three: magnetic induction, electrostatic and piezoelectric; among these three mechanisms, the one that has received the greatest scientific attention is the piezoelectric transduction. This is because piezoelectric materials have larger power densities and higher feasibility for practical applications than the other two mechanisms; furthermore, piezoelectric materials are available for any application area, even microscopic applications. The piezoelectric converters exploit piezoelectric effect that is understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials. In fact, piezoelectric materials exhibit the property that if they are mechanically strained, they generate an electric field proportional to the strain; conversely, when an electric field is applied then the material undergoes a strain [5]. In other words, the piezoelectric effect is defined as that reversible process for which materials exhibit generation of electrical charge due to an applied mechanical force (direct effect) and, at the same time, generation of a mechanical strain resulting from an applied electrical field (reverse effect). Although, there is a wide range of materials that exhibit piezoelectric behavior, the most commonly used materials in energy harvesting applications are zirconate titanate (*PZT*) and barium titanate ($BaTiO_3$) [5]. In the piezoelectric converting methodology, a mass is suspended on a cantilever having a layer of piezoelectric material on top of it. When the mass starts to vibrate, piezoelectric layer is deformed and a voltage is generated. In each application context, it is used a mechanical body in motion and by this movement can be derived sufficient energy to be used in low-power applications.

The Fig. 6 shows the typical scheme of a power harvesting system for self-powered sensor nodes through the use of energy obtained by a piezoelectric harvester. The mechanical vibrations are a potential power source that can be easily accessed through adopting of MEMS technology and related MEMS devices, namely miniaturized mechanical and electro-mechanical elements and structures manufactured by using the techniques of microfabrication.

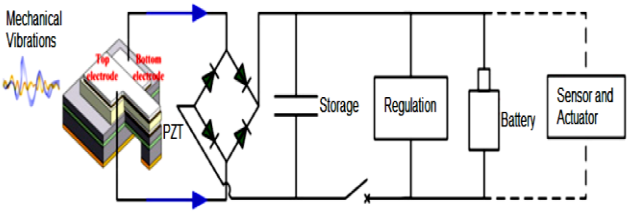


Fig. 6. Schematic diagram of a typical piezoelectric power harvesting system for wireless sensor nodes and actuators.

As example, in Fig. 7 a schematic illustration of a piezoelectric micro-cantilever immersed in a wind flow for flow sensing and energy harvesting is shown [24]. The piezoelectric micro-cantilever consists of a 3mm long and 0.3mm wide piezoelectric beam sandwiched by top and bottom electrodes and a 5μm thick Si supporting layer, as shown in the cross section of the piezoelectric beam.

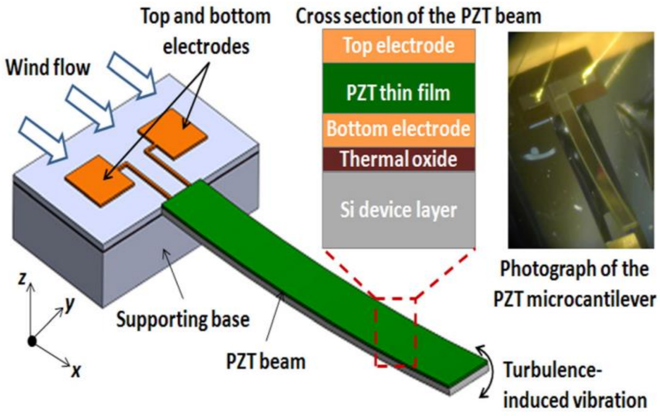


Fig. 7. MEMS technology allows to obtain miniaturized mechanical and electro-mechanical elements making possible the fabrication of micro-cantilevers.

Obviously, piezoelectric devices are available on the market in several dimensions; Fig. 8 reports some of them produced by different leader companies. Usually cantilever-type vibration sensors are loaded by a mass to offer high sensitivity at low frequencies (as shown in the Fig.s 8b and 8c).

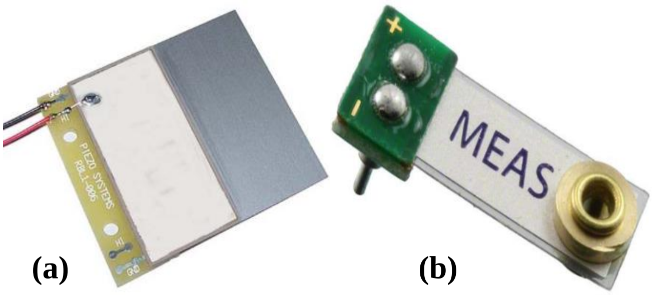


Fig. 8. Piezoelectric devices provided from the main producing companies: Piezo Systems, Inc. (a) and TE Connectivity Measurement Specialties (b and c).

Furthermore, the devices utilizing the piezoelectric effect to convert mechanical strain into electricity can be used in sensing applications in which the devices are subjected to movements or vibrations. They are employed, for example, in health care, where many types of body-mounted or implanted medical devices are required, as wearable devices and also in application where airflow is present, for example in the machines' motion [25]. In this research work, the designed WSN node is not subjected to movement therefore no vibrational energy can be harvested by the sensor; therefore, this energy harvesting technique, although it presents high performances, is not suitable.

2.4 Harvesting systems exploiting magnetic and electromagnetic (EM) energy

Magnetic and electromagnetic energy is another renewable energy more widely available in nature, especially nowadays. Radio-frequency (RF) energy is omnipresent owing to cell phone towers, TV broadcast stations, satellite and radar stations, WiFi routers and other communication networks and it is essentially a free-energy. The magnetic and electromagnetic energy can be obtained by using the complex harvesting circuits and obtained electrical energy, stored within some storage devices, can be used to feed WSN sensor nodes. In recent years, the research based on the technology empowering very small devices, like biomedical implanted devices, low-power wireless sensor nodes, storing the harvested energy in rechargeable micro-batteries and supercapacitors by exploiting the RF ambient energy is more and more of remarkable interest. However, the related output power is very low of the order of 0.1μW/cm^2 and strongly varies with some factors like terrain, number of users, network congestion, etc. [7]. In order to harvest useful levels of electrical energy in these ambient conditions, large broadband antennas with high gain, scalability and easy fabrication are required [26]; for these reasons, this energy harvesting technique is not a good candidate for feeding the designed smart node in this research work. The device used to harvest RF energy is called rectenna, a rectifying antenna used to detect RF signal and then to convert it in a DC output voltage [27]. The sources of usable signals are mainly UHF band (range [885 – 915] MHz), mobile communication systems (GSM) and wireless high-speed network (WiMax) operating in the range [2.4 - 2.48]GHz (ISM band). The Fig. 9 shows the general architecture of an EM energy transducer or harvester.

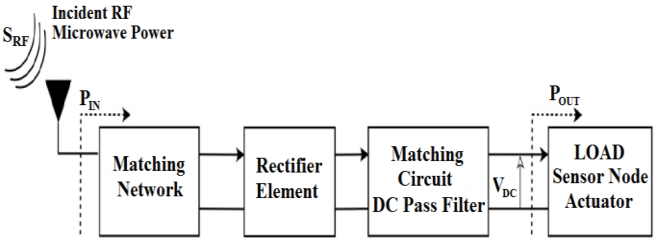


Fig. 9. General architecture of rectifier antenna used for EM Energy Transducer.

Anyway there are many researcher works focused on design of high performances rectennas. Analytical modeling of passive rectifying circuits and the harvesting of electromagnetic energy sources are presented in [28]; the authors showed that, by employing a rectenna with size of ~λ/4 at 930 MHz and a dual-band RF harvester, ambient RF power sources in the range [−27 - −50]dBm from different frequency bands can be exploited to provide perpetual energy for operation of wireless remote sensors requiring 1.3 V as DC supply voltage. In Fig. 10a, the rectenna is used to harvest RF energy for feeding a Thermo-Hygrometer sensor, furthermore in Fig. 10b a rectenna available on the market useful to convert microwave into electricity is shown [28].

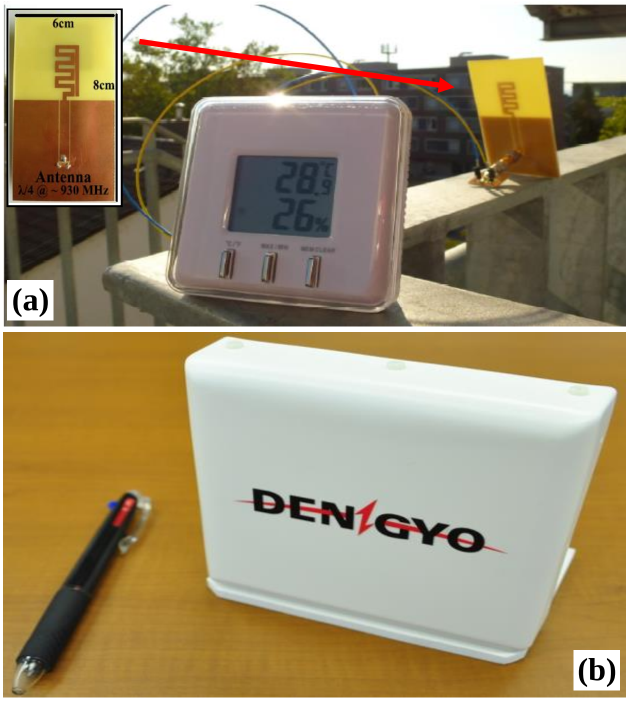


Fig. 10. Rectenna used to harvest RF energy for feeding a Thermo-Hygrometer sensor (a) and a microwave rectenna available on the market, provided by Nihon Dengyo Kosaku Co Ltd, with beside a pen to give an idea of its dimension (b).

2.5 Choice of proper energy harvesting solution for Medimote® power supply

The analysis and studies on the various harvesting techniques combined with the consumption calculation for *Medimote* sensor node allow to have a complete view of the entire set of possible solutions for the harvesting module. A strategy often adopted in application contexts, in which it is possible to derive energy from more types of sources, is the creation of a hybrid harvesting system in order to obtain the required power from the environment to guarantee sensor node functionalities. According to [15], the amount of energy from a single energy harvester is typically small and highly variable with time, its location and working conditions. In order to make the sensor node able to work even when a type of harvesting source is not available, it is possible to design an energy harvesting system that can harvest energy simultaneously from different sources. However, the creation of a hybrid harvester is still accompanied by increased circuit complexity and must find a compromise between storable power, area of device and circuit complexity. Before choosing to use more types of harvesters, the advantages of a combined solution must still be estimated; in fact, a significant increase of complexity for storing energy from two different harvesters could be a wrong choice if one of the two allows to store a negligible amount of energy respect to the other one. The power consumption of Medimote sensor node are rather high and the application context in which the sensor nodes have to operate does not allow the use of a circuital solution that implements an RF harvester. RF electromagnetic energy available in port scenario is very small and it can be assumed absent in a first approximation.

Also the TEG solution is not viable because the temperature difference between the two surfaces of the thermoelectric generator should be instantaneously high; moreover, devices should be extremely bulky to have reasonable power for the case under examination with thermoelectric generators. As regards the use of mechanical vibration, this energy source is one of the most used nowadays and could represent a possible solution. The use of piezoelectric materials, however, would enable the energy storage only when the sensor nodes, applied on or into the containers, are in motion or in any case subject to mechanical vibration from external agents. Furthermore, the device that collects energy from vibrations should work always near a fixed resonant frequency to maximize the energy harvesting. The collectable energy from this technique would not allow to obtain a sufficient amount of electrical power to guarantee an acceptable autonomy of the sensor node. For this reason, the solution that most of all is suitable to be implemented for power supplying the WSN node are solar cells, by means of which it is possible to obtain high power even when using cells of a few cm^2. As previously cited, some commercially available solar cells are very compact and permit to have sufficient energy to feed sensor nodes that require high power during normal operation.

Solar cells available on the market have dimensions that can easily adapt to very small devices like wireless sensor nodes; for example, considering the size of Medimote and its package, a cell like that shown following in Fig. 16a can be used by covering the total area of realized sensor node without requiring additional surface. The use of a cell to be integrated on the sensor node, however, requires a redesign of the position of the on board sensors. The decision to use small solar cells is also justified by the fact that containers, once entered the port area, are placed in the area assigned by the control center, so they are usually placed in outdoor areas that may be subject to solar energy. After choosing the suitable energy harvesting source, some Linear Technology (LT) ICs were analyzed, exploiting dedicated LT demo-boards. The IC device that more than others presents characteristics suitable to be implemented in this context is the LTC3330, specifically called “nano-power buck-boost DC/DC with energy harvesting battery life extender”. This type of IC smart converter was chosen because it can also be used with other types of sources for future development and other application contexts. Moreover, the entire circuit solution aims to ensure that, when no solar energy is available, the sensor node functionalities are preserved for a period of time strictly correlated to the amount of solar energy stored in the supercapacitors. The choice of the LTC3330 IC has been performed exploiting its input and output features that allow to obtain an harvesting circuit board easily adaptable to other WSNs and sensor nodes.

3. WSN for Goods Transport and Storage: Block Scheme and Operation of Designed Smart Sensor Node

The continuing development of WSNs and their flexibility extend the application contexts that can be investigated using sensor nodes. The developed harvesting system has been optimized and characterized for Medimote sensor node (shown in Fig. 13b) with the aim to reduce utilization of backup batteries for feeding the sensor node. The project goal is the creation of a logistics management system based on the use of innovative WSN in order to reduce the need of human intervention. The application context is shown in the Fig.s 11 and 12; the sensor node has the purpose of monitoring some parameters related to the environment in which containers are located and also related to stored goods inside the container and finally to send them to control center exploiting the local gateways.

Fig. 11. Application of designed WSN based on realized sensor node: a scenario for monitoring and managing of goods stored in the containers.

The main components of the scenario are the following:

- WSN node with the purpose of monitoring physical parameters concerning goods stored in the containers and sending these data to the control center. It is possible also to send alarms if a parameter should exceed a set threshold.

- Input or access gateway: it takes care of associating a sensor node to each container; containers will be routed inside the port area using GPS coordinates sent from command center.
- Mobile platform placed on handling machines: the control center will manage the information flow to request the intervention of removal or handling of a container.
- Local gateway placed in each storage area: it manages the data transmission with the control center for all nodes of the same area, from and toward each node placed into the container.
- Control center: it allows the user to perform all operations and to manage various steps or events that can occur in the scenario.

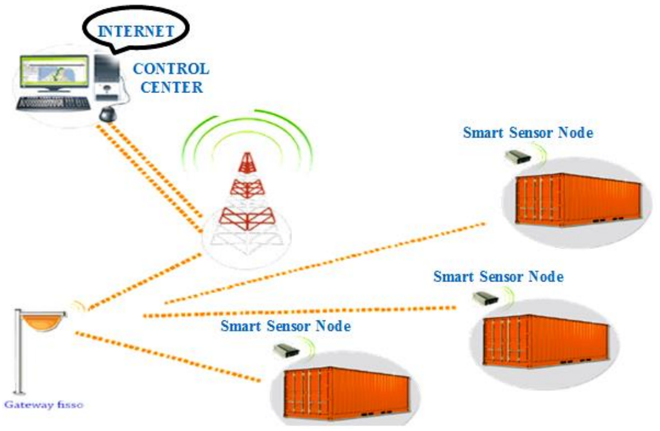


Fig. 12. Typical application of designed WSN applied to containers for the monitoring of stored goods.

The energy harvesting system must allow to the sensor node to carry out required operations rightly in every condition [15-17]. For this reason, two different power supplies are used, the first associated to the harvester and the other, a backup battery, to support node when no power is available from harvesting block. The block diagram and a hardware view of sensor node, including the processing unit, wireless module, a storage unit, on board sensors and digital/analog external inputs, are shown in the Fig. 13, with the main devices or sections highlighted [37, 38].

The processing unit, a Microchip PIC24F32KA302 16-bit microcontroller with extreme low-power consumption, is specially designed for battery powered systems/applications. As regards on board sensors, the Sensirion SHT25 device is provided for temperature and humidity measurements based on capacitive-type humidity sensor and band gap temperature sensor. A light sensor is also present, the Taos TSL2581FN device, with a very-high sensitivity light-to-digital converter that transforms light intensity to digital output signal with I^{2}C interface. The designed sensor node has embedded a MMA8452Q accelerometer, a low-power three-axis micro-machined accelerometer with 12 bits of resolution. The wireless module is a Digi International XBee device with a working frequency of 2.4GHz, a data rate of 250kbps using a direct sequence spread spectrum modulation. This component is critical with reference to power consumption, requiring, most of all other devices, power in the data transmission phase.

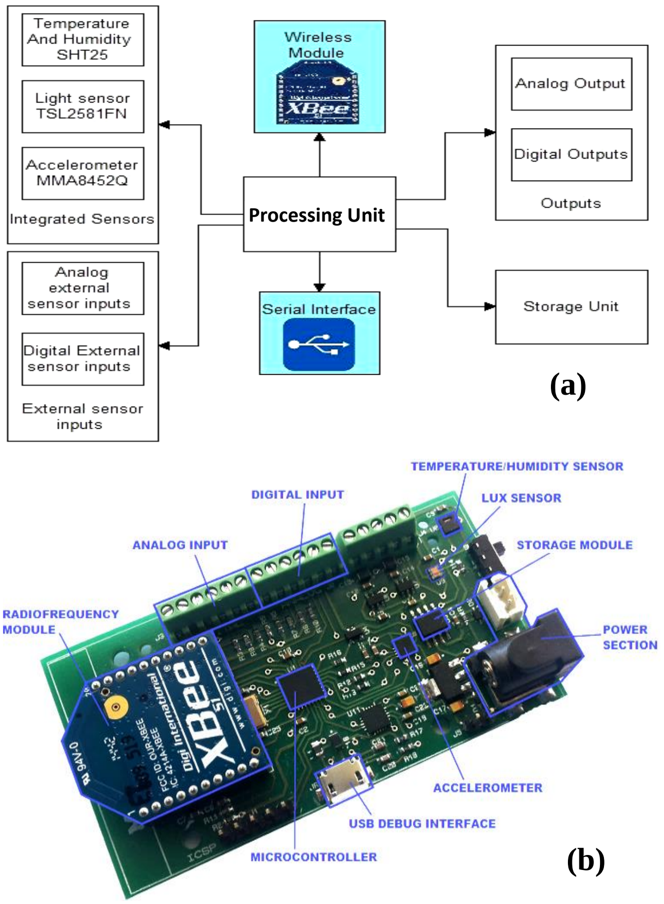


Fig. 13. Block diagram of the designed and realized Medimote® sensor node (a) and hardware view of the SMT-based sensor node with highlighted the principal electronic embedded components (b).

4. Design and Testing of Solar-Based Harvesting and Power Management System for the Medimote® Sensor Node

The challenge in WSNs field is to provide high-performances sensor node self-maintained in terms of energy and possibly low cost [39]. Thus, different energy sources have to be employed to store an energy quantity to make sensor node energetically self-sufficient in its entire life-cycle.

First step to reduce sensor node power consumption is to set XBee transmission module in sleep mode during on board sensors interrogation and data storage. In fact, component that most of all requires power, when sensor node is active, is the XBee module and thus it is useful to activate this module only when data transmission or reception is required. The possibility to make a sensor node completely autonomous in terms of energy depends on several factors including its hardware complexity. According to [40] and based on this application context and power requests of WSN node, mote life-time can be increased more efficiently by solar-based harvesting system rather than other sources available in outdoor scenarios.

After an extensive review, the IC device that more than others presents suitable characteristics is the nano-power LTC3330 buck-boost DC/DC converter (in Fig. 14 the block diagram is shown), specially designed for energy harvesting and WSN applications, with battery life extender, allowing us to design a harvesting board easily adaptable to other WSN nodes. The LTC3330 IC integrates an energy harvesting power supply (EHPS) plus a DC/DC converter powered by a primary battery; the EHPS, consisting of a full-wave bridge rectifier and a high voltage buck converter, allows to harvest energy from piezoelectric, solar or magnetic sources. Moreover, either side of the bridge can operate independently as a single ended AC or DC input.

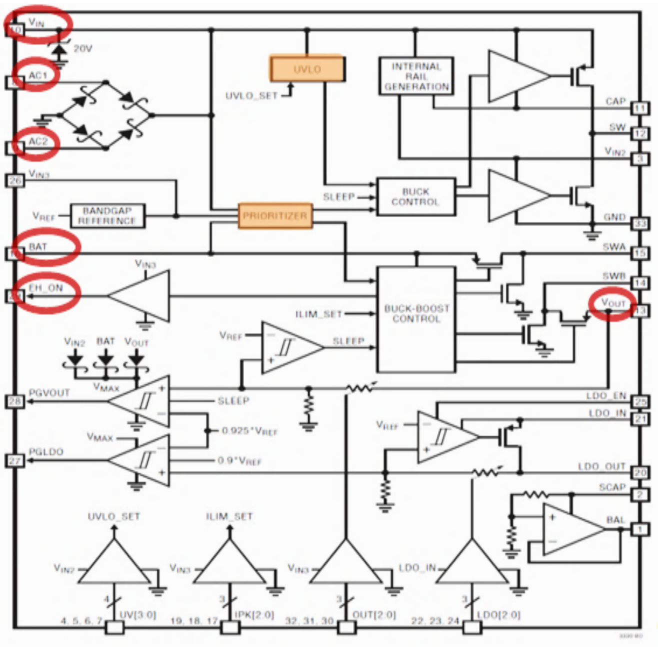


Fig. 14. Internal block diagram of LTC3330 IC provided from Linear Technology: highlighted the I/O pins cited in the following and the principal circuital sections.

Thus, the LTC3330 combines a buck switching and a buck-boost switching regulator: the buck operates when harvested energy is available reducing current absorption from battery to zero, thereby extending the battery life. The buck-boost section powers V_{OUT} only when the harvested energy goes away: the converters are controlled by a prioritizer that selects which converter to use based on harvestable energy availability. A digital output EH_{ON} is used to understand if sensor node power supply is given by backup battery or harvestable energy (low logic level when the prioritizer selects battery input). An important feature is the buck under-voltage lockout (UVLO) and its programmable thresholds: when V_{IN} voltage (from energy source) rises above UVLO rising threshold (settable by UVLO Selection Bits), then the buck converter is enabled. The experimental setup to characterize the DC2048A Demo-board (shown in Fig. 15b) based on LTC 3330 and the related plots captured by means of the oscilloscope are shown, respectively, in the Fig.s 15a and 15c.

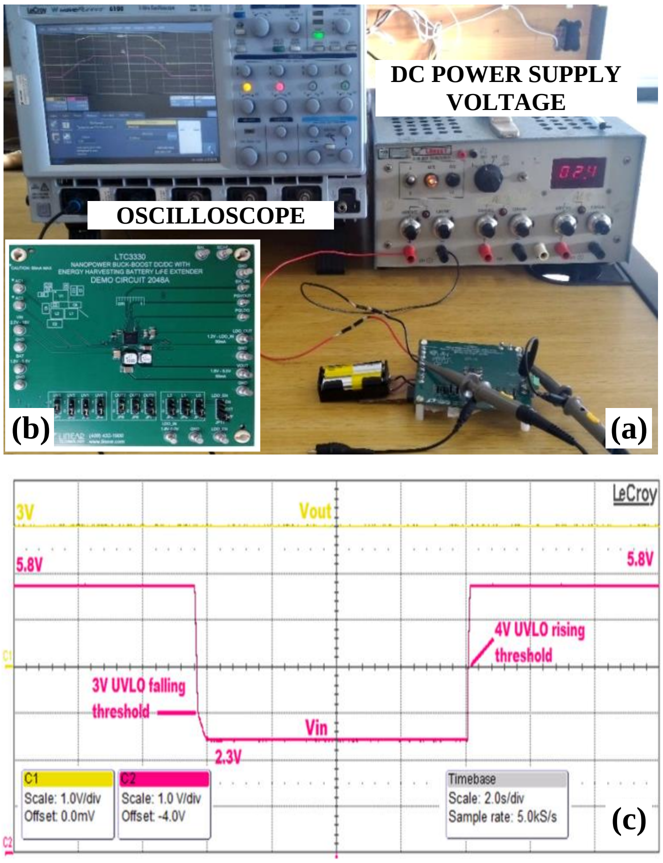
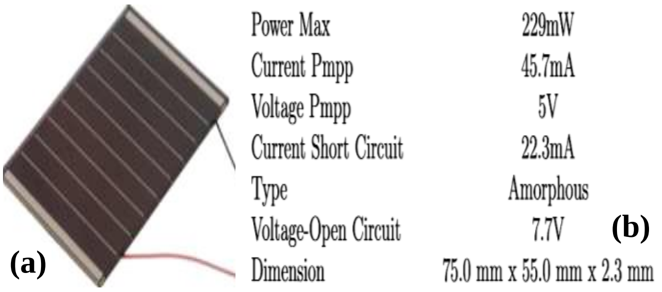


Fig. 15. Measurement setup (a) realized to detect the voltage values of the principal pins of Demo-Circuit 2048A (Buck-Boost DC/DC converter with Energy Harvesting Battery Life-Extender based on LTC3330 IC) (b). Oscilloscope plots related to harvester shutdown test: LTC3330 Vout set to 3V (yellow colour) and DC-supply output voltage (in place of the solar cell) connected to LTC3330 Vin pin (red colour) (c).

Figure 16 shows the chosen commercial solar cell and, in the table, its physical and electrical features. The decision to use small solar cells is also justified by the fact that containers, once entered the port zone, are placed in outdoor area assigned by the control center, so they are subject to solar radiation.



Power Max	229mW
Current Pmpp	45.7mA
Voltage Pmpp	5V
Current Short Circuit	22.3mA
Type	Amorphous
Voltage-Open Circuit	7.7V
Dimension	75.0 mm x 55.0 mm x 2.3 mm

Fig. 16. Panasonic BSG AM-5907CAR used solar cell (a) and its physical and electrical features (b).

By using LTC3330 IC, a complete circuital solution was designed (shown in Fig. 17), able to ensure the following properties:

- Maximum power point control based on UVLO block;
- Supercapacitor charging when more harvesting energy is available respect to the required one by the sensor node;
- Priority control using LTC3330 internal prioritizer for sensor node power supply (harvester or backup battery);
- Backup battery to ensure node operation during start-up phase or long periods of harvestable energy unavailability;
- Regulated DC-DC output voltage to feed the Medimote sensor node.
- AC1 and AC2 inputs of the DC2048 second stage can be connected to a second type of harvester (piezoelectric, solar, or magnetic sources) creating a hybrid device able to accept more types of energy harvesting sources. Therefore, even if for the Medimote sensor node the best choice is represented by solar cells, the designed circuit accepts in input different types of energy harvesters as allowed by the IC LT3330.

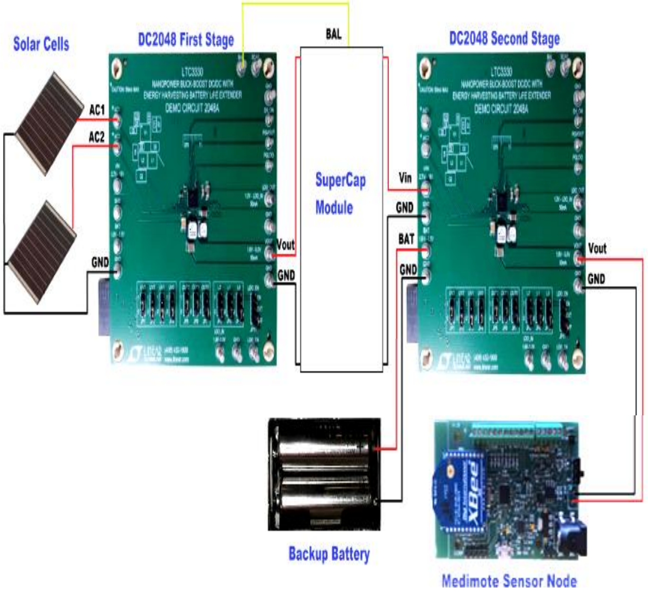
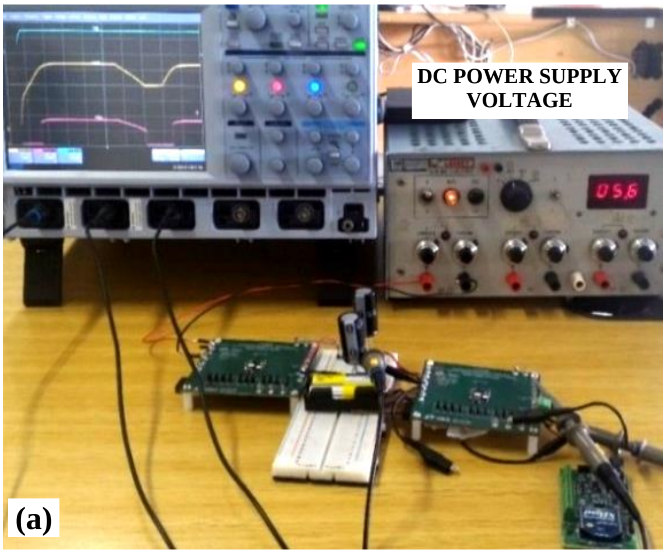


Fig. 17. Harvesting circuit prototype composed of two DC2048A stages, a supercapacitor module, the backup battery and the realized Medimote® sensor node.

Figure 18a shows the measurement setup to characterize the energy harvesting prototype composed of two DC2048A demo-boards (shown in Fig. 17). The DC power supply (output current limited to 40mA) is located upstream the harvesting circuit (with energy source function) and the mote (as load) is connected to the prototype output. In Fig. 18b, the captured traces by using the oscilloscope are shown: in blue, the output voltage V_{out} of second stage, in yellow the voltage across the super-capacitors V_{scap} and in red the EH_{ON} pin. When there is energy availability from the harvester, this energy is stored into the super-capacitors connected to first stage output; if V_{scap} exceeds the rising UVLO threshold (4V), then the second DC2048A stage feeds the node with stored energy. Furthermore if solar cells provide enough energy to charge supercapacitors up to 4.5V, then a direct connection between solar cells and node is established. After, if solar cells are unable to provide sufficient energy to sustain node consumption, capacitor voltage V_{scap} begins to decrease until it reaches UVLO falling threshold (3V) and the LTC3330 prioritizer of second stage will decide to feed sensor node through backup battery. In this way, the supercapacitor is disconnected from the second stage and charged by the energy provided by the solar panel; when the voltage on supercapacitor rises up to 4V (in few minutes even with non-optimal lighting conditions), the backup battery is disconnected (the supercapacitor is reconnected) thus increasing its life-time. Furthermore, super-capacitors charging phase up to 4V, when system is connected to the solar cells, lasts few minutes even with non-optimal lighting conditions. The goal is to decrease, as much as possible, the slope of supercapacitors discharge phase in order to maximize the energy autonomy in absence of harvestable energy, so minimizing the use of backup batteries.

In addition, in order to extend the life-time of the battery, the harvester managing board allows to harvest energy from a variety of alternative energy sources by exploiting the main properties of the LTC3330. The microcontroller, the main system of a sensor node, has the task, beside the others, of optimizing sensor node from an energy point of view; in order to reach this goal, it is possible to set the sensor, or the other part of hardware, in low power or sleep mode. In this way, power consumption is reduced and therefore batteries lifecycle can be extended.

In experimental test shown in Fig. 18a, supercapacitors are charged up to 4.5V through the DC power-supply; then, this last is turned off to simulate the absence of harvestable energy, causing supercapacitors discharging (V_{scap} from 4.5V to 3V). When V_{scap} goes below UVLO falling threshold, EH_{ON} pin becomes low (previously it was high ensuring node supply by supercapacitors stored energy).



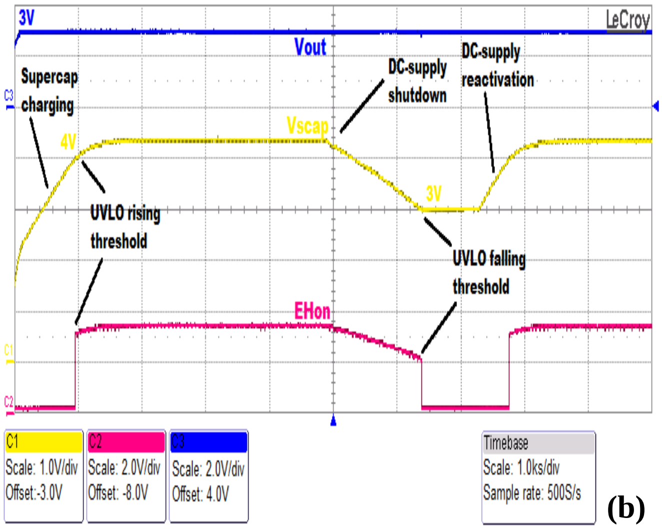


Fig. 18. Experimental setup for prototype test: the DC power supply connected to the input of DC2048 first stage and the Medimote sensor node in output (a). Output voltage measured before Medimote node Vout (blue colour), supercapacitors voltage Vscap during DC-supply functioning and shutdown (in yellow) and EH_{ON} voltage in red (b).

5. PCB of Harvesting and Power Management System: Test and Characterization

After verifying the proper functioning of energy harvesting prototype, the related PCB with mostly SMT devices was realized: as shown in Fig. 19, the different circuital sections are pointed out together with selection jumpers that allow to adjust different thresholds or output voltage values [41].

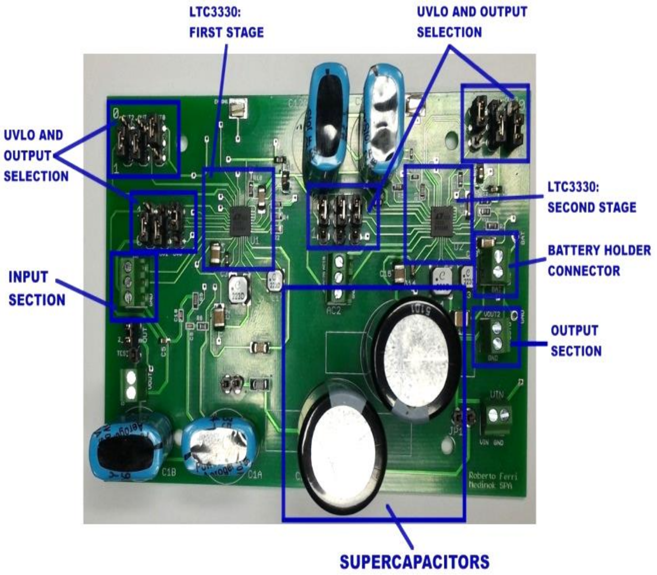


Fig. 19. Realized PCB of designed harvesting and power management board for low-power sensor node with indicated the principal circuital sections.

A final verification of the harvesting board functioning using Panasonic solar cells as energy harvesting source was carried out. The realized experimental setup is shown in Fig. 20a, the 229mW small-size solar cells are shown in the inset (Fig. 20b) and the graphs detected by oscilloscope in Fig. 20c, in particular during late afternoon or equally in case of high sun coverage. The super-capacitors are charged up to 4.5V, the chosen output voltage of first LTC3330 stage: then, the solar cells are covered causing the decrease of Vscap and later still the solar radiation level is not enough to feed the sensor node being late afternoon.

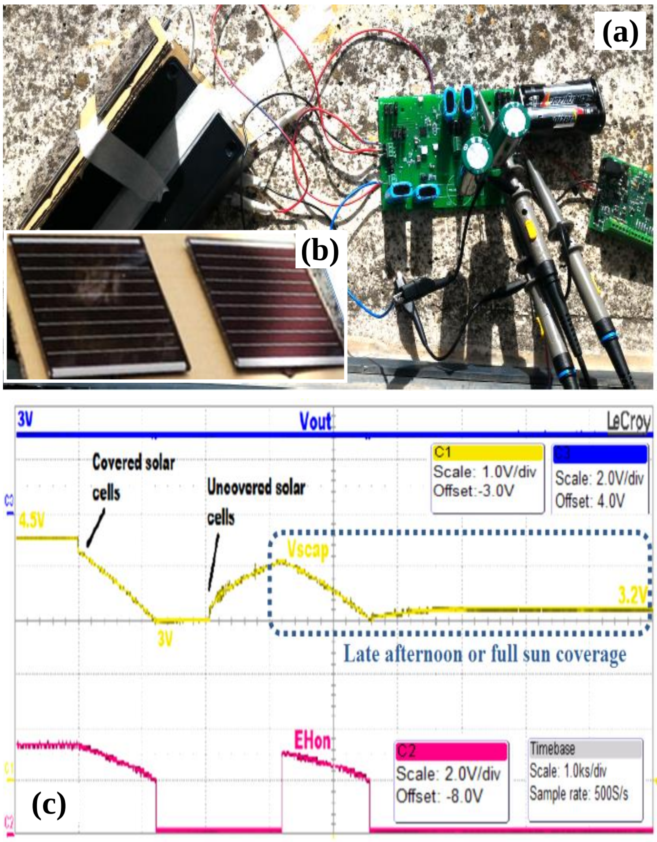


Fig. 20. Experimental setup for electrical testing of final harvesting system (a). Panasonic solar cells connected to inputs of realized PCB (b). Plots captured by the oscilloscope during late afternoon or in case of sun coverage: voltage before node Vout (blue colour), supercapacitor voltage Vscap (yellow) and in red, EH_{ON} voltage trace (c).

The carried out experimental tests have confirmed the proper functioning of realized harvesting system with harvestable solar energy greater than that required for node functioning in daytime, with normal and not-critical weather condition. Moreover, the use of higher super-capacitor values improves the node energy autonomy without involving backup batteries in case of no harvestable solar energy (up to 3,5 hours for supercapacitors value of 100F).

By exploiting CSV data of Vscap during the discharge phase, an analysis related to few operating cycles was carried out: as evident in zoomed area (Fig. 21b), voltage decreases faster when the node is active (transmission phase for 10sec) and a high current is required; instead the voltage decreases slower when the node is in sleep mode (time duration of 50sec).

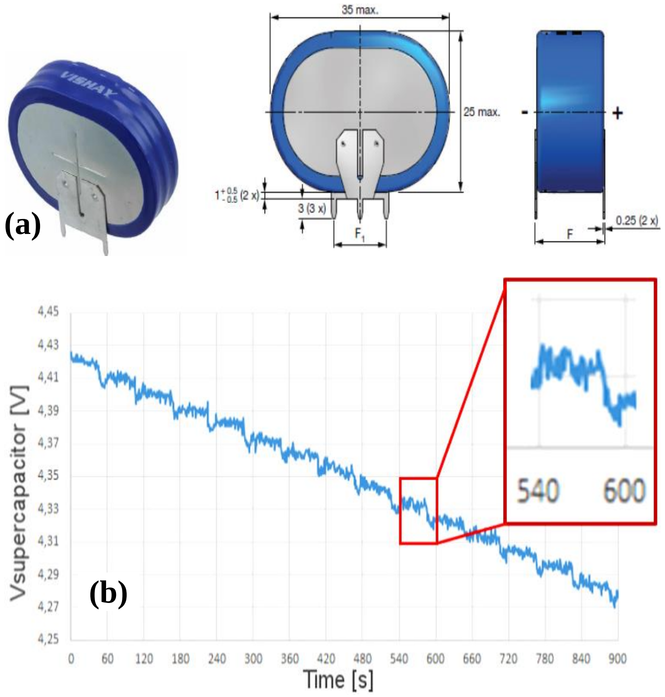


Fig. 21. Example of commercial stacked hybrid super-capacitors for energy storage with reported the package dimensions in millimeters (a) and detailed analysis of super-capacitors voltage discharge with C_{TOT} equal to 100F (b).

Following, a justification regarding the choice of system components is reported. Obviously they were chosen as function of the specific application and scenario where the sensor node will be employed. The harvesting solution has been obtained exploiting the DC2048A Demo-Circuit; solar cells selected for the harvesting section (Panasonic BSG AM-5907CAR model) present I_{MPP} = 45,7mA and V_{MPP} = 5V. Their choice was determined from DC2048A demo-circuit input characteristics and from their physical dimensions comparable to the Medimote sensor node. Also the supercapacitors were chosen in order to satisfy the required supply voltage from the sensor node and to reduce the time interval in which the backup battery is activated, thus increasing the life time of the battery itself. In particular, in the performed tests, capacitors of 30F and 100F were used in order to obtain respectively equivalent capacitance values of 15F, 50F and 100F exploiting series and parallel connections. The aim was determine the autonomy time, when no harvestable energy is available, for different supercapacitors values, by measuring the discharge time during the transition of voltage across supercapacitors from 4.5V to 3V. Medimote autonomy, using C_{TOT} of 15F, when no harvestable energy is available from solar cells, was equal to 25min; with C_{TOT} = 50F, a discharge time of more than one hour (exactly 75 min) has been measured, before the prioritizer of the second LTC3330 stage decides to activate the backup batteries; instead, using a C_{TOT} equal to 100F, the discharge time amounts to three hours and half. This approach helps to reduce backup batteries use even on days with discontinuous availability of the harvestable energy.

Obviously, by adopting a greater solar panel and supercapacitor, compatibly with the sensor node dimension, it is possible to increase the life time of the backup battery by reducing the number of times when it is connected. Furthermore, as reported in the LTC3330 datasheet, the IC enables the use of supercapacitors in energy harvesting applications. Moreover, supercapacitors present a lower cost compared to that of batteries and have higher power density than batteries, but have lower energy density. An important factor is related to the charge/discharge cycles: in general, though batteries are good for between one and ten thousand charge/discharge cycles, supercapacitors are rated for between ten thousand and 100,000 cycles, hence they are suitable to be applied in energy harvesting applications. Supercapacitors tend to degrade more quickly at higher temperatures, compared to batteries; typically, they are specified up to +70°C, whereas, many batteries are specified only up to +60°C. Supercapacitors are much better than batteries at handling current surges, but their output drops off rapidly with load. On the other hand, supercapacitors have relatively high internal self-discharge, so even if they are not used, there will be loss of stored energy. Depending on model, they can discharge through this leakage in about a month, and so need frequent replenishment; in contrast, battery self-discharge is on the order of 10 percent a year. Therefore, the final choice, in our developed system, is to combine both types of storage elements in order to obtain the best performance for the designed sensor node.

In Fig. 22, the final package of designed harvesting board is shown; it has two inputs for solar cells' connection to AC_1/AC_2 input pins of first LTC3330 stage and one output for the node feeding.

Fig. 22. Final structure of realized harvesting board for WSN node power-supply.

The developed system can be adapted to other application contexts and WSN nodes: energy source's inputs consist of a full-wave bridge rectifier and a high voltage buck converter, allowing to harvest energy not only from solar cells but also from piezoelectric, magnetic or electromagnetic sources and in general from AC power sources. Inside the package a battery holder is used to insert backup batteries.

For a comparison between our obtained results and other results present in literature, some recent works related to the energy harvesting for power supplying WSNs are analyzed following. Reference [42], for example, describes a combined energy-aware interface with an energy-aware program to deal with the mismatch through managing the energy flow from the energy storage capacitor to the WSNs. Unlike our work, in which the sensor node requires 59mA during data transmission phase and about 7mA during the sleep phase, a piezoelectric energy harvester under an emulated aircraft wing is used and a power equal to 3.2mW is generated in [42]. Reference [43] reports that making WSNs for environmental monitoring is still a challenging and complex task, despite advances in electronics, network algorithms, power efficiency, and energy storage. Each situation requires from the engineers and system designers to pick one or a few energy harvesting methods based on the system and location limitations. In this context, the photovoltaic methods, chosen in our work, are quite effective, especially when perovskite materials are used, as suggested by the authors, but are heavily dependent on light conditions. In [44] the current consumption of the designed wireless sensor node is 103.3mA and only the solar energy is used for feeding the WSNs; in this work, in place of a supercapacitor and a backup battery, a Li-Po rechargeable battery and two LM317 voltage regulators are used in order to charge up the Li-Po battery and to provide the proper supply voltage to the node. In conclusion, the IC LTC3330 used in our research work seems to be the best choice also because this IC allows to exploit several sources of energy when available; the use of the LTC3330 is also suggested by the authors in [1], which, after an overview on the different energy sources available surrounding the electronic systems, in the conclusion section they indicated the LTC3330 chip as a convenient solution in order to build a WSN at a reasonable cost.

6. Conclusion

We have reported on the design and testing of an energy harvesting board applied to WSN for goods transport and storage monitoring. After an overview on the principal energy harvesting techniques available on the market and on the technological trend related to new energy harvesting solutions, the solar energy was chosen as energy source for feeding the designed smart node being the technique that, more than the others, allows to satisfy the technical and power requirements of the proposed WSN. The realized harvesting PCB is able to fully power supply the sensor node, by exploiting solar energy, in daytime with normal weather condition. Developed harvesting system can be easily adapted to other application contexts and WSN nodes; also, depending on scenario and kind of available energies, any harvester can be chosen and connected to the harvesting PCB for ensuring the sensor node operation.

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