Energy harvesting for Autonomous Wireless Sensors and RFID's

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Abstract

Energy harvesting technologies are receiving significant interest from industry and academia as they provide a foundation, an enabling technology towards the realization of 'zero-power' wireless sensors and implementing the Internet-of-Things (IoT) and machine-to-machine (M2M) communication. The principles of commonly used energy harvesting technologies such as solar, piezoelectric, thermal and electromagnetic are listed and design challenges and novel technologies and materials, such as paper, textiles, and large volume inkjet printing fabrication are presented. Hybrid–multiple technology harvesters are discussed and the development of low profile antennas and rectennas, integrating an electromagnetic radiator with solar cells and a thermoelectric generator are presented. Optimal signals suitable for wireless power transmission are discussed.

1. Introduction

Numerous research efforts have been recently directed towards low profile, low power, energy efficient and self-sustainable sensor networks aiming to harvest ambient energy from vibrations, as well as solar and thermal energy, and finally microwave energy from existing employed communication networks. Table 1 presents indicative performance results from different types of energy harvesters. Electric energy generation using different transducer types is a vast field with many different applications and large variation among the size of the transducers and the amount of energy that is being generated. As a result the final selection of the employed type of transducer depends greatly on the application requirements and scenario, which makes the presented results of Table 1 only indicative of the potential of the various harvesting methods. Table 1 places emphasis on low profile transducers suitable for micro-power generation.

Table 1. Indicative harvested power values from different transducer types.

Energy source	Harvested power	Conditions / Available power
Light / solar	60 mW	6.3cm x 3.8 cm flexible a-Si solar cell. AM1.5 Sunlight (100 mW/cm^2) [1]
Kinetic / Mechanical	8.4 mW	Piezoelectric shoe mounted [2]
Thermal	0.52 mW	Thermoelectric generator (TEG), $\Delta T = 5.6K$ [3]
Electromagnetic	0.0015 mW	Ambient power density 0.15 uW/cm^2 [4]

Photovoltaic technology explores the photovoltaic effect in order to convert solar energy to electrical energy. The discovery of the photovoltaic effect is attributed to A.E. Becquerel [5], who discovered in 1839 that certain materials generate electrical current when exposed to light. Thin film technology both reduced material costs and allowed a much larger size of the unit of manufacturing compared to the first generation unit size which was limited to the wafer size [6]. Third generation photovoltaic technology combines the low cost fabrication of thin film technology with novel design concepts able to lead to much higher efficiencies [6]. Solar cell efficiency tables containing the maximum measured efficiencies of solar cells and solar modules are published periodically [7].

Kinetic energy harvesters convert energy from mechanical movements to electrical. There is a large number of applications that can be classified under this category as there are many different types of mechanical movements such as vibrations, displacements, and forces or pressure, and consequently different types of transducing mechanisms. One may identify applications related to buildings and other construction projects such as bridges, exploring vibrations originating from a plurality of sources such as near-by or on-going car automotive or train traffic, human movement wind, heating, ventilating and air-conditioning (HVAC) air currents, water and other fluid movements [8]. Vibration energy can be harvested in moving vehicles such as cars, trains, ships and airplanes by properly installing transducers in sensitive places of the vehicle, such as the wheels of the car for example. There are three transducing mechanisms that are used to convert kinetic energy to electrical energy: a) electrostatic (capacitive), b) electromagnetic (inductive) and c) piezoelectric. A great challenge in the vibration to electrical transducer design is that of maximizing harvested energy by controlling the natural frequency of the transducers. There are several different possibilities proposed in the literature which include transducers with mechanically or electrically tunable resonant frequencies and self-tuning or adaptive tuning capability on one hand, and wideband and multiband arrays of generators on the other hand [8, 9].

Thermoelectric transducers convert thermal energy into electric energy. Thermal energy is generated as a result of a multitude of phenomena and applications, in some cases intentionally but most of the time as waste heat from a process or reaction, from industrial plants to buildings, heating systems, automobiles to the human body, which, in turn, provide numerous applications for thermal energy harvesters. There are three thermoelectric phenomena that govern the conversion of thermal energy to electrical energy and vice-versa: a) the Seebeck effect, b) the Peltier effect and c) the Thomson effect [8,10]. Thermoelectric generation is based on the Seebeck effect where a temperature gradient between two different metals or semiconductors that are in contact creates a voltage difference between the two components [8,10]. Due to the fact that semiconductors offer much higher values of Seebeck coefficients than metals and metal alloys, thermoelectric generators (TEGs) are built using semiconducting materials. They are usually constructed by forming arrays of pairs of p-type and n-type semiconductor pellets. The pellets are electrically connected in series using conducting (for example copper or aluminum) strips, and are sandwiched between thermally conductive ceramic plates [8,10].

The concept of power transmission by electromagnetic waves has initially appeared in the works of Hertz and Tesla [11]. Subsequently, in the second half of the twentieth century and beginning in the late 1950s the use of microwave signals to transfer power which can subsequently be converted back to DC has been considered in applications such as the microwave powered helicopter and the concept of solar power satellite with microwave transmission to earth [11]. The circuit that is used to convert electromagnetic power to DC power is the rectenna, which was patented by W.C. Brown in 1969, and consists of an active antenna combining a radiating element (antenna) with a rectifier circuit [12]. These initial applications of microwave power transmission focused on scenarios where directive, high power transmission is required. The recent interest in autonomous sensors has led to the concept of ambient electromagnetic energy harvesting or scavenging where rectennas are used to provide DC power by converting to DC available power from existing ambient low power electromagnetic sources not specifically transmitting to power a sensor [13]. The amount of DC power that can be harvested from the existing available power is proportional to the rectenna RF-to-DC efficiency η. The rectenna efficiency varies with the different rectifying circuit topologies and devices used and it is dependent on the available input power and the load resistance at the rectifier output. Rectifier circuits typically use Schottky diodes to convert microwave power to DC power. Low and zero barrier diodes are required in order to rectify low power input signals, similar to the ones used in detector applications. Typically envelope detectors and charge pump circuits are implemented. Reported rectenna efficiencies at UHF frequencies for available input power levels in the order of 10 uW (-20 dBm) are between 15% - 25%, and increase to 40%-60% for available power levels of 100uW (-10 dBm) [13,4].

Each transducer technology has distinct advantages and disadvantages, and is thus suitable in different application scenarios. Solar energy generally represents the largest energy source, provided however there is sufficient light, which makes its use challenging in indoor scenarios, and during night or cloudy conditions. Thermal energy harvesters are typically limited by a low transducer efficiency, while kinetic energy harvesters are sensitive to the natural vibration frequencies of the harvester and application settings. Finally, the available electromagnetic (EM) energy density is usually orders of magnitude below the corresponding values of the other energy sources, although recent publications in crowded urban settings have shown the possibility of harvesting a useful amount of EM energy from the ambient [14-16], especially using wideband or multi-band harvesters. Despite of the low ambient EM energy densities, electromagnetic harvesters are intimately related to systems exploring intentional EM radiation to power up electronic devices, which leads to numerous applications of wireless power transfer, with radio frequency identification (RFID) technology being a notable application example. Due to the large variation of available ambient energy of the various types, the implementation of energy autonomous circuits for communication and sensing dictates the integration of multiple energy harvesters, which are highlighted in the following section.

2. Multi-technology harvesters (thermoelectric antennas, solar antennas and electromagnetic energy harvesters).

The integration of different types of harvesters under the condition of low profile implementation, poses several challenges, one of which is associated with the fact that the amount of harvested power increases with the size of the harvester while cost and other mechanical limitations require a small size. A characteristic example is the introduction of the solar antenna in [17], in order to minimize the utilized area for solar energy harvesting and communication antennas in micro-satellites. The original paper introducing solar cells integrated with a patch antenna paved the way for numerous implementations of different types of antennas integrated with solar cells, with early examples from JPL [18] and EPFL [19]. The recent interest in battery-less sensors has spurred a number of novel, compact, solar antenna and rectenna designs in the literature, while the combination of new technologies and newly used materials for RF electronics has led to the implementation of a variety of new designs. A recent example is shown in Fig. 1 where a substrate integrated waveguide (SIW) cavity backed slot is integrated with two amorphous silicon a-Si solar cells with a plastic protective cover on top [20], while a textile solar antenna was demonstrated in [21]. Inkjet printing fabrication has led to several novel implementations of RF circuits and antennas, and an example of an active antenna implementing a UHF beacon signal generator powered by solar cells placed on top of the ground layer of a folded slot antenna is shown in Fig. 1 [22]. Recently the integration of a thermoelectric generator on top of a shorted patch antenna built on FR4 substrate, operating at 2.45 GHz was demonstrated (Fig. 2) [23].

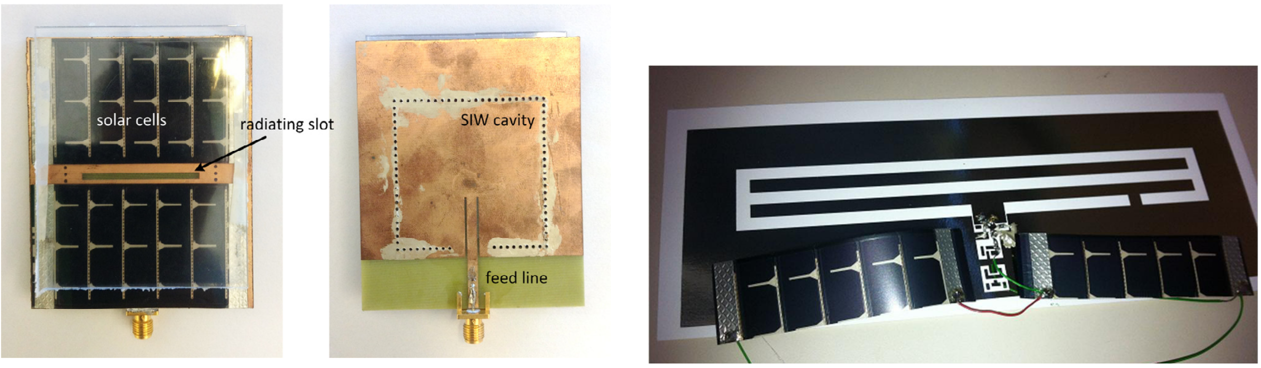

Fig. 1 Solar SIW slot antenna [20] (left), and inkjet-printed active oscillator antenna powered by solar cells [22] (right).

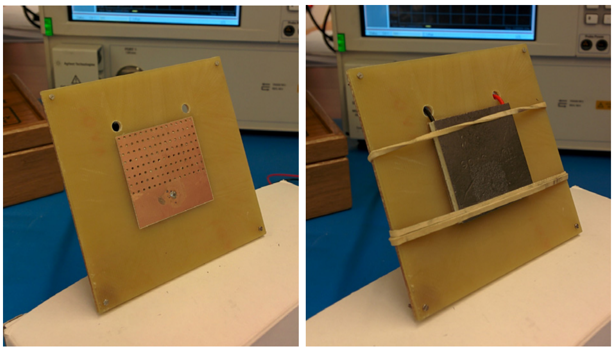

Fig. 2 Patch antenna integrating a thermoelectric generator (TEG) [23].

3. Rectennas and wireless power transfer

The interest in wirelessly powering sensors and electronics by transmitting or harvesting EM power has led to the design of rectennas with optimal RF-DC conversion efficiency by studying different rectifier circuit topologies as well as different antenna topologies considering different polarization, gain, and impedance bandwidth scenarios. In addition to circuit challenges, one may consider the properties of the transmitted signal in terms of their average power and peak power levels and the effect they have on the rectifier efficiency. As a result, it was shown that multi-tone signals [24] and generally signals with a time varying envelope may lead to improved efficiency. Recently a range of signal types including ones with multi-carrier modulation such as OFDM, white noise and even chaotic signals [25], were shown to provide improved rectifier efficiency paving the way for waveform optimization specialized to wireless power transfer (Fig. 3).

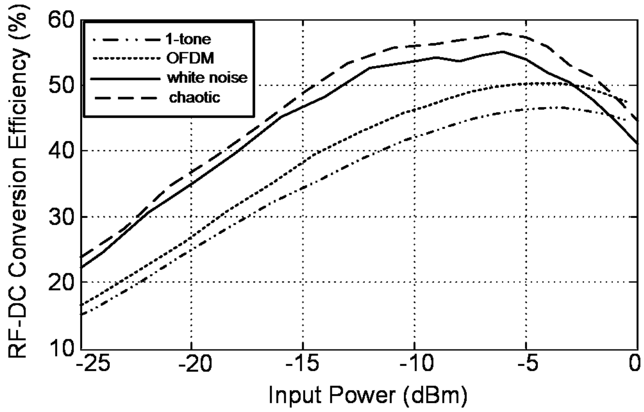

Fig. 3 Rectenna efficiency for different types of RF signals [25].

4. Conclusion

Energy harvesting technologies provide an exciting possibility for autonomous operation of wireless sensors and communication. In this paper, a summary of commonly used technologies is presented, and technical challenges and recent developments are identified.

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