ENERGY HARVESTING SYSTEMS: THEORY AND PRACTICAL DESIGN

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ABSTRACT

Energy harvesting emerges as a promising technology for the development of future digital communications regarding the paradigm of green communications. In this scenario, the most relevant characteristic is the use of renewable energy to power wirelessly electronics devices in a microwatt scale. By means of this technology several advantages are achieved in the field of wireless communications. Self-powered systems are developed to increase battery lifetime and to achieve lower operating cost. The main applications are reported in the fields of wireless sensor networks, cellular network, as a key component for the deployment of 5G, in radio frequency identification (RFID) systems to asset tracking, and in cognitive radio paradigm. The major problem is that energy sources are time-variant and unpredictable, which in turn causes several constrains in the processing capability of these devices. RF sources are presented as an attractive solution since it does not depend on nature and it provides relatively predictable energy supply. In this sense, the current article is addressed to model theoretically RF energy harvesting systems and describe the main limitations and practical issues. Several solutions are analyzed with the objective to improve performance and reliability. The mainly components of harvesting nodes and the practical considerations of circuits design are also described. Open challenges are presented as guideline of future researches.

KEY WORDS: Energy harvesting system, green communications, cooperative networks, cognitive radio.

1. INTRODUCTION

The accelerated deployment of digital systems, including its processing capabilities, functionalities and services, demands bigger amount of energy each year. Some reports exhibit that 2-3% of the world electricity in 2007 is consumed by the Information and Communication Technologies [1]. In 2009 the International Energy Agency (IEA) reported that the power consumption of electronic devises at home such as televisions, laptops and mobile phones represents the 15% of the total power and it is rapidly increasing [2]. Besides, analyzing the evolve of hardware elements from mobile computing, the improvement of the main elements of a digital system are growing in a similar rate except by the battery capacities that represents the slowest growing curve, as depicted in Fig. 1 [3]. In this scenario, energy harvesting systems have emerge as a promising technology related to green communications. Several reports and products are focused on this field from both academic and industrial research communities.

Energy Harvesting circuits are designed to gather energy from the environment and to convert this to power electronic devices in a microwatt scale. This technology is orientated to the development of self-powered devices and to increase the use of renewable energy sources in wireless communications and networking [4]. The original idea of wireless power transmission was developed by Nikola Tesla, who had the vision of freedom energy transfer between two points without the need of wires. The pioneering work dates from 1969 when an small helicopter, powered by an RF source reaches the 50 feet [5].

In 2009 the market for energy harvesting applications was valued for 79.5 million USD, and this value has grown to 45 million USD by 2009 [6]. By way of example, wireless charging systems will have a market of 4.5 billion by 2016 and this value was estimated to be tripled to 15 billion in 2020 [7]. Other reports exhibit a market of 1894.87 million USD by 2017 and growing at a rate of approximately 24% [8]. The leading manufactures for smartphone devises like Samsung, Apple, Huawei are introducing their products with built-in wireless charging capability [3].

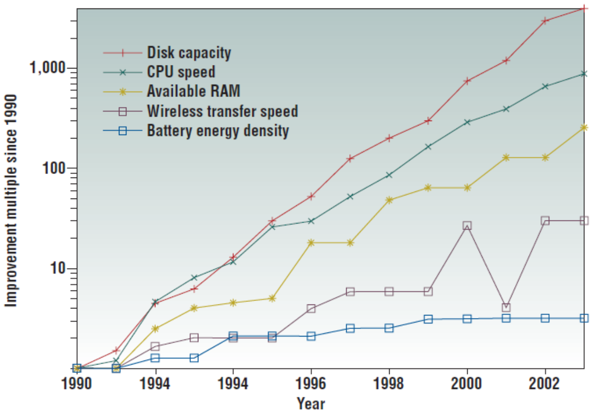


Figure 1: Improvement in computing technology [3].

Energy harvesting provides several advantages for wireless communications including wireless batteryless nodes with self-sustainable capability. This guaranty an uninterrupted operation to a massive number of sensors and electronic devices that support the development of several emerging applications like Internet of Things (IoT), 5G cellular networks, cognitive radio and others [4] [9]. Besides, this system improves the performance of communication networks in a variety of aspects such as longer device lifetime and lower network operating costs. Main applications are summarized as follows:

1. Wireless Charging Systems: low-power mobile, electronic watches, hearing aids, MP3 players, wireless keyboard and mouse [7].
2. Wireless Sensor Networks: Networking, smoke detectors, door locks, smart meters, industrial reactors, chimneys, subterranean locations [6], environment and ambient monitoring [10], healthcare applications [11], smart grid, building automation, surveillance [12], agricultural management [13], habitat monitoring [14].
3. Machine to Machine Communications [8].
4. Asset Tracking: Wireless identification and Sensor Platform for identifying, locating and track people, assets and animals through the use of RF identification (RFID) systems, inventory management and long-range asset tracking for automobiles, trucks and trains [15].
5. Cellular networks: 5G cellular networks incorporating harvesting energy technology to both base stations and communication devices [4] [16].
6. Cognitive radio [4].
7. Vehicular networks [17].

Several energy sources are available for these systems. These are grouped as: Solar/Light, Thermoelectric, Mechanical Motion/Vibration, Electromagnetic Radiation. From these sources, RF energy emerges as an attractive solution since it does not depend on nature and it provides relatively predictable energy supply [4].

This article is addressed to model theoretically RF energy harvesting systems and describe practical considerations of circuits design. The rest of the article is outlined as follows. Section 2 analyzes the available sources of RF. Section 3 describes mainly components of harvesting nodes. Section 4 models theoretically RF energy harvesting systems, presents the major constrains and summarizes reported solutions. Section 5 analyses cooperative systems with focus on cognitive radio. Finally, future line of researches are presented on Section 6.

2. RF ENERGY HARVESTING SYSTEM

Energy harvesting systems has some drawbacks in regard to electrical power grid. Available energy sources are time-variant and unpredictable, which in turn limits the processing rate of systems. Hence, the principal goal is to find the best power allocation sources and to optimize the relation between energy consumption and harvesting rate. In this sense, RF energy presents some advantages, since it is considered as relatively predictable and controllable source if the receiver is static. However, if the receiver is in motion the harvested energy could be random [4]. Besides, RF energy is broadcast transmitted by several current technology such as: DTV, GSM900, GSM1800, 3G, Wifi, in which the Wifi source is the lest contributor [18]. RF energy harvesting nodes are typically comprised by an energy harvesting module to collect energy and by an information transceiver as shown in Fig. 2. The energy-harvesting module has to gather RF energy from the environment and convert it in an adequate DC level in order to power the device.

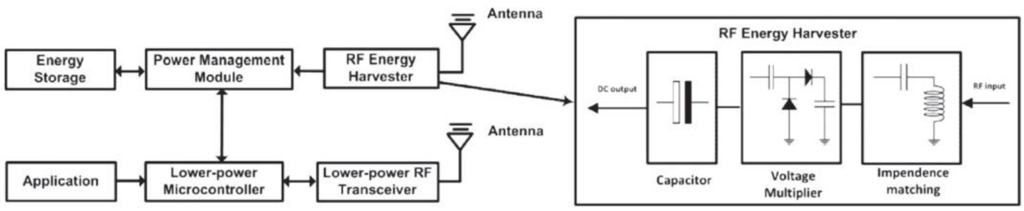


Figure 2: General Architecture of energy harvesting devices [19].

The amount of harvested energy from RF signals depends on the transmitted power and the channels effects like path loss, shadowing and fading. The power transmitted and received by these sources are summarized in chart 1. The power received at the output of the antenna is computed taking into account the Friis's transmission formula on a logarithmic scale as [20]:

$$P_R = P_T - L_P + G_T + G_R \qquad (1)$$

where P_R and P_T are the received and transmitted power, G_T and G_R are the transmitter and receiver gain antenna and L_P represents the free space past lost given by:

$$L_P = 32{,}4 + 20\log_{10} f + 20\log_{10} R \qquad (2)$$

f is the operating frequency in MHz, R represents the distance in kilometers. Additionally, the sum $P_T + G_T$ is called the Effective Isotropic Radiated Power (EIRP). This expression assumes no additional lost as multipath effect. In a real environment, the received power is attenuated in power of R^{-2} to R^{-4}.

Chart 1: Power transmitted and received by each different source.

Sources	**Band**	**Transmitted Power**	**Received Power**	**Distance**
TV broadcast	80-220 MHz	few tens of kW [21], 70 dBm [22]	-40 dBm -17 dBm	In natural environment 6,6 km
FM broadcast	88-108 MHz	few tens of kW [21]		
AM broadcast	540-1600 kHz	few hundred of kW [23]		
ISM band	902-928 MHz	4 W (36 dBm) [19]	-16 dBm [36] -20 dBm [37]	> 10 m 20 m
Mobile GSM	800 MHz	1 W to 2 W [21], 4 W of maximum power [24], -43 dBm (18 dB antenna gain) [25]	-20 dBm to -35 dBm [42,48] [38] -110 to -53 dBm [39]	20 m
Wireless LAN	2.45-5.8 GHz	10-20 W per carrier [21] 100 mW [26]	-38 dBm	5 m

3. CIRCUIT DESIGN

The energy-harvesting module as shown in Fig. 2 is mainly comprised by five different elements: antenna, impedance matching network, rectifier, booster circuit and load.

Antenna:
There are different design based on dipole, loop, planar, meander, spiral, microstrip and Yagui-Uda antennas. Given the wide distribution of different RF sources and with the aim to extract maximum power from the environment, an ideal design is a high gain wideband antenna. As described above, the most common bands for energy harvesting are 614 MHz (DTV), 900 MHz (GSM900), 1800 MHz (GSM1800) and 2400 MHz (ISM band). Several solutions are addressed to develop multiband antennas to harvest energy in each band of interest [27]. Additionally, another aspect to keep in mind is the non-desirable effects that limits the antenna performance such as multiple reflection, changes of direction and the fact that the source of the RF signal comes from unknown locations.

Several techniques can be implement to solve these issues by means of omnidirectional radiation patterns in the azimuth plane, multiple polarized antenna, Multiple Input and Multiple Output (MIMO) or Multiple Input and Simple Output (MISO) systems. MIMO and MISO systems are commonly employed since it allows to estimate the Direction of Arrival (DOA) and adaptively conforming the radiation pattern (DBF) in order to recover maximum energy from the environment. This is known as Adaptive Smart Antennas Systems. DOA estimation methods allows to compute the elevation and azimuth angles. On the other hand, adaptive beamforming adjusts the main beam of radiating patterns taking into account DOA information. The main algorithm used are Least Mean Squares Algorithm (LMS) and Recursive Least Squares Algorithm (RLS). The former exhibits less complexity, which in turn leads to a low computational cost. However, this method shows to have higher convergence's time. RLS algorithm solves this problem but complexity is increased.

Impedance matching network:
The circuit is implemented to adjust the output impedance of the antenna with the input impedance of the rectifier and guarantee maxima power transfer. At the same time it is comprised by a resonator circuit, which performs similar a bandpass filter centered in the frequency of operation. This circuit also rejects the harmonics generated by the rectifying circuit to be reradiated by the antenna [5].

Rectifier:
This element transforms the RF pulse into Direct Current (DC) with a specific voltage level. It is mainly supported by diodes. Several topologies are used as a cascade of diode-capacitor stages in order to obtain a voltage multiplier circuit. This increase the DC voltage and power electronic devices in a typical voltage range of 1-3 V [5]. The reported solutions employ diodes of series HSMS-282x [28], HSMS-285x [29], HSMS-286x [30] and SMS7630 [31]. The HSMS-285x is not recommended for higher power level applications (> -20 dBm).

Booster Circuit:
Booster circuit is used to transforms and managing the output voltage from the rectifier step. Usually this is employed for raising the output voltage and powering the electronic devices supervising the charge of the output capacitor. These devices are also named as Power Management Module (PMM). This is used for converting the DC voltage at the output of the rectifier into a DC voltage through a maximum power tracking procedure for optimal energy extraction. Devices often employed are BQ25504 [32], LTC3108 [33], Seiko S-882Z [34] and AS-1310 [26]. The most commonly used are BQ25504 that has an input voltage of 330 mV, output voltage of 1.8 V and achieve an efficiency of 70-90 %.

Load:
Energy harvesting systems are designed for low power consumption devices guaranteeing the maxima efficiency between the harvested energy and energy consumption. The principal devices reported are:

- MSP430F2247-CC2500 [35]: The MSP430F2274 is a low-power 16-bit microcontroller, and the CC2500 is a low-power 2.4 GHz transceiver. On average, the radio transmission task consumes 13.14 mA for 3.4 ms, the power needed for this device is in the order of 20mW (13 dBm).

- WISP (Wireless Identification and Sensing Platform) [36]: This are small sensor devices with a power consumption in the range 2µW to 2mW (-26 dBm to 3 dBm). The WISP is used for interfacing sensors such as light, accelerometers, temperature and for RFID and wireless security research.
- MICA2 sensor mote [24]: This sensor has integrated an Atmel ATmega128L microcontroller. The circuit is powered with 1.8V and 30 µA for 54 µW (-12 dBm).
- Temperature and humidity meter (Radio Shack) [36]: This device is integrated with and LCD display and usually consumes 25-50µA at 1.5V, which in turn gives a maximum consumption power of 75 µW (-11 dBm).

4. THEORETICAL DESCRIPTION OF ENERGY HARVESTING SYSTEMS

The theoretical description of energy harvesting systems comprises the analysis of the channel capacity as well as energy transmission modeling. Channel capacity is modified by the availability of the harvested energy. Energy transmission modeling concerns how to transmit not only information but also energy.

Energy harvesting systems can be represented as a classical communication AWGN channel with zero-mean, unit-variance Gaussian noise N, input X and output $Y = X + N$ codewords, augmented with an energy source E_i as depicted in Fig. 3.

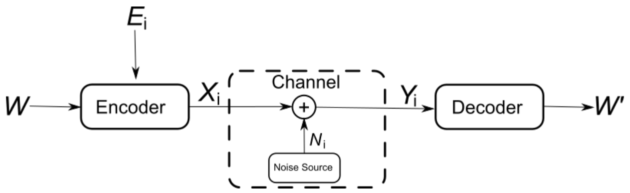


Figure 3: Energy harvesting system.

Taking into account that during the i-th element codeword transmitted the energy arrives stochastically as a stationary and ergodic random process E_i , energy consumption is constrained by the available harvested energy given by:

$$\sum_{i=1}^{t} {X_i}^2 \leq \sum_{i=1}^{t-1} E_i \tag{3}$$

As long as the available sources are time-variant and unpredictable then the Shannon's channel capacity is limited. This is called energy causality constraints on the channel input [37].

According to this constrain there are three protocols reported to be used in the harvesting energy and usages process: harvest-use (HU), harvest-store-use (HSU), harvest-use-store (HUS) [4]. The first protocol is not supported by batteries, implying that the harvested energy at the i-th time instant is directly used to transmit information and is consumed only on that time instant. This means that incoming energy is either used or lost. In this case, data is transmitted only when sufficient amount of energy is acquirable to cover the processing cost.

Harvest-store-use (HSU) protocol supports in battery to increase system performance. However, some practical issues are needed to be considered as the efficiency in storing energy, the energy leakage from the storage device, the basic processing cost at communication nodes and the sleep-and-awake mechanism [4]. In this case, the harvested energy is firstly stored and then is employed by the device. Then, the amount of energy for data transmission ${X_i}^2$ is limited by the stored energy and the processing cost.

In harvest-use-store (HUS) protocol both, the harvested energy from the environment and the remaining energy after processing and transmission process are stored. The maximum available energy for transmission is constrained by the harvested energy and the available energy in the battery.

According to [4] the HUS protocol has a better achievable rate than the HSU protocol, while the two protocols achieve the same performance if maxima efficient in the storage process is considered.

The channel capacity of an energy harvesting system is only described in the following three cases:

- Unlimited-sized battery ($E_{max} = \infty$) [38]
- No battery ($E_{max} = 0$) [39]
- Unit-sized battery ($E_{max} = 1$) [40]

In case of unlimited-sized battery two schemes are presented in [38], namely save-and-transmit and best-effort-transmit. In the former one, the system first harvest and store energy from the environment in a battery with infinite capacity, which implies that an infinite amount of energy could be saved. Thus, the capacity of the channel is not constrained. In the later one, the capacity is constrained by the available energy and the information is only sent when the battery has enough energy.

In more practical scenarios with finite capacity battery there are some issues to considers like energy outage and energy overflow. Energy outage describes the case when energy is required by the system to keep operations but the battery is empty. This is the main constrain that limits the capacity of the channel as described in equation (3). On the other hand, if the system harvests energy that is not consumed by the device, then once the battery is full, the remaining harvested energy is lost. This is call as energy overflow and causes inefficiency in the harvesting process [4].

The above protocol evidenced the close dependence between information transmission rate and energy harvesting rate, for that reason the main goal is to optimize the time allocation ratio between energy harvesting and information transmission. This is related with the fact that the transmitted symbol affects the amount of available energy in the battery and demands energy harvesting. On the other hand, the available energy at the battery imposes a restriction under the allowable set of symbols that can be transmitted. In this sense, there are different solutions addressed to transfer information and energy jointly or independently.

Some architectures propose to transmit information and energy independently by using different antennas for energy harvesting and information reception, which in turn implies that two different receiver circuits can be implemented. This is an useful scheme given that the sensitive parameter of a circuit to harvest energy is not the same that the used to receive information. In this case, two different circuits are used to maximize their respective operating efficiency. Typical information receiver operates with a sensitivity of –60 dBm receive signal power, while an energy receiver needs up to –10 dBm signal power. In addition to the one-way scheme, there are other solutions orientated to full-duplex communications as shown in Fig. 4. In this case, the harvester circuit may recover energy from the own transmitted information [4] [9].

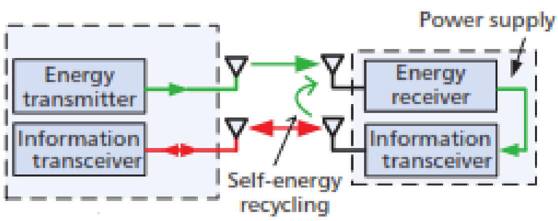


Figure 4: Full-duplex communications scheme [9].

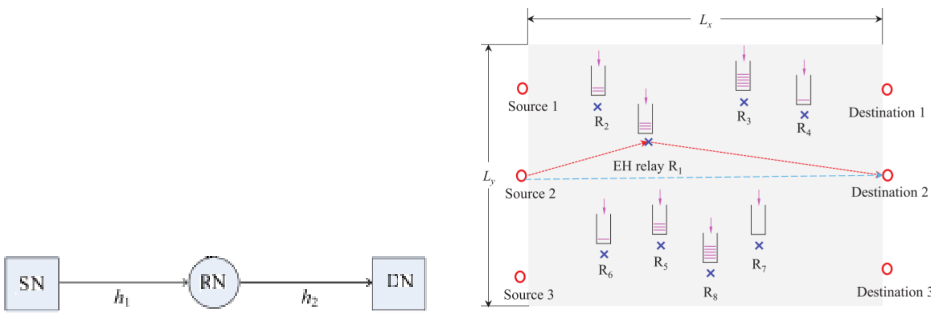
Additionally, energy and information transmissions can be performed either in an out-of-band or in-band manner. Transmitting in different bands guarantee to avoid interference, however this requires more spectrum resources. Although transmitting in the same band guarantees spectrum efficiency, additional protocols are needed in order to avoid interference. According to this, there are several solutions, which propose to deliver energy and information simultaneously. There are two reported approaches: time-sharing and power-splitting. In time-sharing, information and energy are separated in different time slots. In power-splitting, the received signal power is divided into two parts, for energy harvesting and information processing. The former is most practical, provided it allows to employ two separated receivers optimized with adequate power sensitivity [4].

Other important issue in harvesting system is to conform a model to describe potentialities of the available energy and allow to design an energy schedule plan. Deterministic or stochastic models are mainly adopted according to prior knowledge information. Deterministic model supports non-causal knowledge of Channel State Information (CSI) and Energy State Information (ESI), assuming prior knowledge of energy arrival instants and the amounts of harvested energy. It is used to characterize the optimal energy scheduling strategies and provide a benchmark of the fundamental performance limits of energy harvesting systems.

On the other hand, stochastic models is developed by more practical assumptions since it is based on statistical information of the instantaneous energy arrival rate. There are some solutions based on Markov chains of first order to model energy packet arrival, but owing to the randomness of energy harvesting process it is difficult to create an accurate model [4]. Two energy scheduling are proposed: offline and online. Offline scheduling assumes that energy is already available [41][42] and online perspective assumes a statistical knowledge of the instantaneous energy arrival rate and channel gain [8][43].

5. COOPERATIVE ENERGY HARVESTING SYSTEM

Novel lines of research are orientated to develop information and energy cooperation in order to improve the reliability of wireless communication systems. This system is based on sharing spectrum and energy among all networks nodes with the objective to solve the major energy harvesting systems limitations. Information cooperation guarantee robustness against fading in the channel, since a virtual MIMO systems is created to support spatial diversity and to improve energy efficiency at the same time. Considering a two-hop communications scenario comprised by a source node (SN), a relay node (RN) and a destination node (DN), where the destination node is far from the source node as depicted in Fig. 5(a). The objective is to transmit data packets from the source node to the destination node maximizing the end-to-end throughput of the system supported by the relay node. The process can be analyzed in three-time slots: firstly, source and relay nodes harvest energy from the environment; secondly, source nodes transmit data and energy to relay nodes in order to guarantee enough available energy for retransmitting. On the third stage, the information is delivered to the destination node. To optimize this process the source node must be able to determine the sufficient and necessary amount of energy to be transferred to the relay node, such that at the end of the transmission session there will be no remaining energy and any remaining data packets in the relay node.



(a) (b)

Figure 5: Cooperative energy harvesting systems: (a) Two-hop communication scenario (b) Cooperative communication scenario comprised by 3 SN-DN pairs and 8 RN [44].

According to [4] the cooperative transmission scheme represents a better solution in case of poor energy arrival rates whereas direct transmission scheme is suitable for high energy arrival rates. Energy cooperation allows to transfer energy in a wireless manner for one node to other. This improves battery lifetime and provides a relative stable amounts of energy, which in turn guarantees continuous operations and increases the end-to-end throughput.

Assuming more practical scenarios with several pairs of sources nodes and destinations nodes, the use of several relays nodes to assist the communication between the source and destination improves the system gain in energy and spatial diversity as depicted in Fig. 5(b) [44]. Reported in [44] a novel and low-complexity algorithm is proposed to minimize the maximum transmitted power among all sources and destinations pairs. In this scenario, the relay selection is one of the biggest challenges in order to satisfy QoS constrains and it is based on the available energy in each relay node.

The above schemes are useful in cellular networks, multi-users networks and cognitive radio networks. In the next sub-section, cognitive radio is developed in more detail.

Cognitive Radio Applications

Cognitive radio is an attractive solution to deal with the scarcity of spectrum resources by improving the efficiency in the use of the medium. Secondary Users (SUs) identifies spectrum holes given by inactive periods of Primary Users (PUs). These holes in the spectrum are used to transmit information. In this scenario, energy harvesting proposes a new paradigm by utilizing information and energy cooperation techniques to increase energy and spectral efficiency of cognitive radio.

In these systems, the SU must develop spectrum sensing techniques in order to determine the unused bands and then access the channel and transmit information. For that reason, optimal spectrum sensing and channel access policies are developed in order to maximize throughput with the harvested energy available on the battery. The correct selection of some parameters as sensing duration or detection threshold becomes crucial in this design [4]. According to this, in [45] an optimal sensing and channel access probability to maximize the network throughput is proposed. This is performed in a scenario composed by multiple SUs that share a common primary channel. The method takes into account that energy harvesting and spectrum sensing processes are accomplished separately in time. Once the harvested energy exceeds a predefined threshold then the system determines according to a sensing probability, based on the believe of the PU activity, whether a sensing algorithm must be applied to the channel or not. As a result it is shown that access probability does not influence the end-to-end throughput when sensing probability is optimal chosen.

In [46] a new protocol applied to cognitive radio networks for multiple PUs is proposed. In this scenario, SUs harvest energy from PUs and share the spectrum resources in an underlay paradigm. This implies that is not needed to realize sensing protocols since SUs can transmit as long as the interference at PU does not exceed a

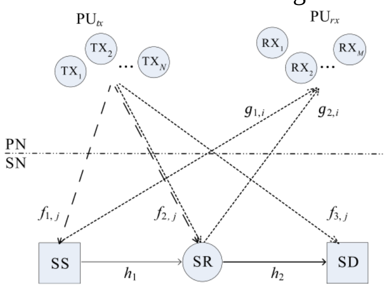


Figure 6: Cognitive radio application with multiple PUs [46].

predefined threshold. A Secondary Source (SS), Secondary Relay (SR) and a Secondary Destination (SD) comprises the SUs networks as depicted in Fig. 6. On this figure dashed, dotted, and solid lines denote the energy harvesting links, interference links, and information links, respectively. The main contributions is to obtain an exact expression for the outage probability and propose some practical considerations to improve network performance. As a result, an optimal number of PU transceivers is given to achieve a tradeoff between the minimum outage probability and the maximum throughput of SUs. It is also demonstrated that when the PUs approaches the SS and get away from SR and SD, then more energy will be harvested at SS, while the interference imposed on SR and SD will be decreased as well as the outage probability.

6. CHALLENGES

Several challenges are identified in the design of energy harvesting systems in order to achieve maximal transference of energy and guarantee maximum end-to-end throughput providing QoS standards. In this sense, main solutions are addressed to find the optimal power allocation based on the knowledge of battery state, channel and energy profiles. This is used to implement optimal policies related to the harvested energy and its employ. Open researches are mainly focused on:

System model:

- An accurate and realistic model to describe channel and energy profiles is needed. This considering data capacity, processing cost, and imperfect CSI in order to design energy scheduling and evaluate the performance of the system [4].
- Shannon's channel capacity formula to describe finite-size battery systems. Current solutions are mainly addressed to unlimited-side battery and unit-size battery [47][37].
- From a wireless communication theory point of view, practical adaptive coding and modulation schemes, and finite block length scenarios are open directions [37].

Robustness:

- Due to the complexity of an accurate stochastic channel model, a proper performance most be achieved with imprecise knowledge of CSI and ESI.
- Efficiency in energy storing and reduction of energy leakage in regard to battery imperfections most be improved.
- New and robust channel coding in order to mitigate the errors induced in the channel and in the processing stage [48].

System performance:

- To design a hybrid system between energy harvesting and power grid in order to increase the QoS to solve the main constrains in the channel capacity simultaneously. This solution is orientated to minimize the grid power consumption and to maintain the system performance at the same time [4].
- Circuit design to employ different kind of renewal energy sources for battery charging in order to increase the amounts of harvested energy [4].
- New algorithm to improve systems performance by minimizing the outage probability and the transmission completion time and to optimize the harvesting and transmission periods.
- New sleeping policies to increase the battery life of harvester nodes.
- In order to improve the energy harvesting efficiency, it is necessary a high gain and directivity antenna for a wide range of frequency, capable of harvest energy even when the RF source is far from the system [33]. Novel antenna design are orientated to MIMO technology.
- Due to impedance mismatching between the antenna and the receiver, the total of the energy harvested is not able to deliver properly. In this case, it is important to design a circuit that automatically tune their own parameters with high sensitivity [33].
- To implement interference management policies and spectrum scheduling.
- To design a receiver to transfer wireless information and power simultaneously [48].

Energy cooperation systems:

- The development of new protocols such as medium access control (MAC), time division multiple access (TDMA), space-division multiple access (SDMA) that allow the correct performance of multi-users networks to avoid interference and collisions, reducing latency and packet loss and increasing the transmission rate [9].
- To design an optimal policy in order to select the relay node in a two-hop or multi-hop energy harvesting system [49].
- Spectrum and information cooperation from game-theoretic perspective [4].

Data Communication [7]

- To implement duplex communication systems that becomes useful when the charger need to request for battery status.
- The obtaining of secure communications protocols to avoid charging and charger device identity steal, as well as the falsification of the charger status.

7. CONCLUSIONS

Energy harvesting system is regarded as a main issue in the development of green communications. This is implemented in order to employ renewable energy sources to power electronics devices. The main advantages are reported in the field of wireless communications including wireless batteryless nodes with self-sustainable capability. Drawbacks of this technology are identified with the available energy sources. Common sources are time-variant and unpredictable. Thus, the processing unit could be interrupted by the energy supply if the energy harvesting system is not properly designed. The current article provides a general description of RF energy harvesting systems. In this respect, several solutions are reported to implement policies to guarantee optimal energy and information transmissions periods with the objective to achieve optimum end-to-end throughput. Energy and information cooperation are also reported as a solution to improve reliability in wireless communications. By means of this technique a virtual MIMO systems is created to provide spatial and energetic diversity, which guarantee robustness against fading channels. Energy harvesting in cognitive radio has emerge as a new paradigm to improve efficiency in the use of energy and spectrum resources. A variety of practical design are reported in the field of intelligent antennas to guarantee maximum power transfer from the environment to the circuit. Open challenges are mainly related to efficiently integrate harvesting and processing units together. In this respect, simultaneous wireless information and power transfer is identified as a great impact line of research.

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