Cognitive Radio Networks with Energy Harvesting Capability: A review on recent advancement

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Abstract—Harvesting energy from ambient sources and converting it to electrical energy used to power devices is of increasing importance in designing green communication networks. The increasing demand for spectral and energy efficient communication networks has spurred a great interest in energy harvesting (EH) cognitive radio networks (CRNs). In this work, an energy harvesting cognitive radio networks(CRNs) are considered, where each secondary user (SU) extract energy via harvesting energy by Radio Frequency (RF) signal of primary user (PU) during sensing time as well as the transmission time of a detection cycle if PU is present. The review of energy harvesting cognitive radio networks is shown. Also the survey of energy harvesting from RF and non RF sources are discussed.

I. INTRODUCTION

The radio spectrum is becoming scarce owing to rapid growth in wireless devices and applications. Moreover, the governance of radio spectrum throughout the world has tended towards exclusivity of its use in large geographical areas, allocating frequency bands for specific applications and assigning licenses to specific users or service providers. As most of the frequencies are now assigned there has been shortage of frequencies that can be assigned to emerging wireless products and services. Furthermore, exclusivity creates underutilization of spectrum, as very rarely can all licensees make full use of frequencies assigned to them. These facts have motivated the search for technologies that can alleviate the scarcity of spectrum and offer new ways to exploit the available spectrum. Cognitive radios emerged as a technology that can potentially alleviate the problem of spectrum shortage.

Cognitive Radio (CR) is a communication design paradigm in which the radio devices equipped with transceivers can sense the underlying radio environment and adapt their transmission/reception parameters like operating frequency, power, modulation rate, etc [1]. The specific instance in which the operating frequency is adjusted is known as Dynamic Spectrum Access(DSA). DSA has the potential to alleviate the spectrum scarcity [2]. CR networks contains two types of users namely primary users(PU) i.e., licensed user that have higher priority on the usage of spectrum and secondary users (SU) i.e., unlicensed users that have lower priority to opportunistically use the spectrum without causing any undue interference to the primary users. Thus, secondary user need to have tendency to sense the spectrum efficiently and check whether the primary user is using the spectrum or not and to change the radio parameters to utilize the unused spectrum.

In conventional energy-constrained wireless communications systems (e.g., wireless sensor networks), energy supply for wireless nodes is always a crucial concern [3]. Traditionally, wireless nodes operate based on batteries that require physical charging or replacement to supply enough energy for their operations and data transmissions. This not only increases the maintenance cost, but also degrades the network performance if there is not sufficient energy supply to the wireless nodes. Recently, energy harvesting has emerged and become an effective way to enable long-term and maintenance free operations of the wireless nodes. There are many forms of energy harvesting including solar, radio frequency (RF), wind, and vibration. Energy harvesting techniques can be adopted in various wireless networks, including cognitive radio networks [4] which can improve spectrum utilization and network performance, and also enhance energy efficiency of secondary users.

Among available energy harvesting techniques, RF energy harvesting is considered as a particularly appropriate solution in a cognitive radio environment because of the following advantages. Firstly, with the rapid development of communications systems worldwide, RF sources are available almost everywhere (e.g., base stations, access points, or even mobile phones), providing pervasive energy supply for secondary users. Secondly, RF energy can propagate and transfer over distance, allowing flexibility for mobile secondary users to gain energy supply. Thirdly, RF energy is broadcast in all directions, and hence multiple secondary users can benefit from the same RF source. Fourthly, the RF energy is controllable by adjusting transmit power at the RF sources. Despite many benefits, using RF energy harvesting in the cognitive radio networks is not straightforward. RF energy becomes a precious resource that needs to be jointly managed and optimized with radio spectrum. Although other forms of energy harvesting have been used in cognitive radio networks, the resource management schemes developed for them cannot be directly adopted for RF energy harvesting.

The remainder of the paper is organized as follows. Section II shows different RF and non RF energy harvesting. In Section III, we summarize system model of energy harvesting that can be applied in cognitive radio networks. Next, in Section IV, we consider throughput maximization, where energy harvests are at the communication slot level, and describe the efforts in identifying the throughput optimal transmission power. In Section V, conclusion and evaluation.

II. OVERVIEW ON DIFFERENT TECHNIQUES OF RF AND NON RF BASED ENERGY HARVESTING

Energy harvesting is the process by which energy is derived from external sources (e.g., RF Signals, solar power, thermal energy, wind energy, salinity gradients, and kinetic energy, also known as ambient energy), captured, and stored for small, wireless autonomous devices, like those used in wearable electronics and wireless sensor networks.

A. Classification of RF Energy Harvesting

Several methods of WPT have been introduced in the recent literature, including near-field short-range inductive or capacitive coupling, non-radiative mid-range resonance, and far-field long-range RF energy transmission. Nonetheless, the latest class of RF energy transmission in the microwave frequency band is the most recently focused technique. In such frequencies, the wavelength of the RF signal is very small and the WPT system does not require calibration and alignment of the coils and resonators at the transmitter and receiver sides. This renders the technique as a suitable solution to power a large number of small wireless mobile devices over a wide geographical area[5].

Due to the specific communication requirements of the cognitive radio nodes and the nature of RF energy harvesting, communication techniques and protocols used in the traditional CRNs may not be directly used in RF-powered CRNs. In particular, it is important to firstly identify the sources of RF energy and their different characteristics in order to understand the technical challenges faced by RF-powered CRNs. The mechanisms by which RF energy is obtained can be mainly classified into two categories: non-intended RF energy harvesting and intended RF energy harvesting. In the following subsections, we provide an overview of these two categories.

1) Non-intended RF energy harvesting: Non-intended RF signals are ambient RF sources not originally intended for energy transfer. This includes signals radiated due to wireless telecommunication services, such as cellular systems, mobile devices, and Wireless Local Area Networks (WLANs), or from public broadcasting systems, such as TV and radio. These ambient signals, if not received by their intended receivers, are dissipated as heat, resulting in a waste of energy. Instead, they could be used as a sustainable and low-cost source to harvest energy.

A device that harvests energy from ambient RF sources can have separate antennas or antenna array for RF transceiver and RF energy harvester. Harvesting energy by this means is subject to long-term and short-term fluctuations due to radio tower service schedules, nodes mobility and activity patterns, and fading. Therefore, cognitive radio terminals should employ new schemes that consider the trade off among network throughput, energy efficiency, and RF energy supply, given the dynamic availability of the RF energy.

The figure below shows model of RF Energy Harvesting.

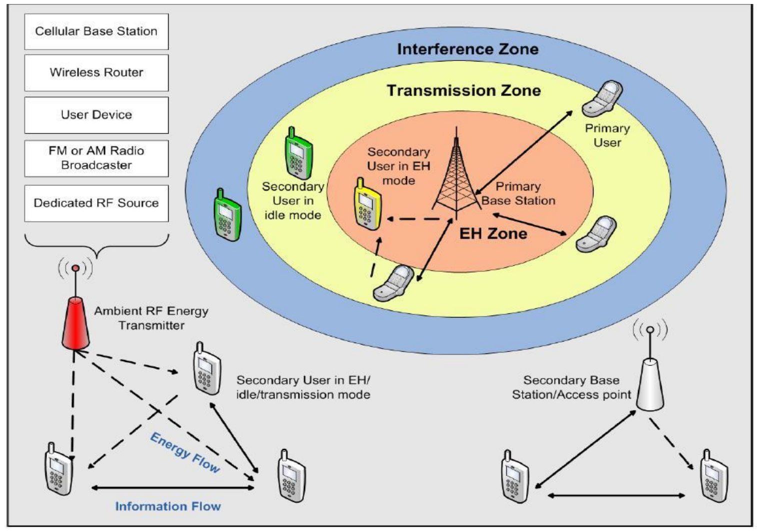

Fig. 1: A general architecture of an RF-powered CRN

2) Intended RF energy harvesting: This method can be divided into two types. In the first, the receiver obtains wireless power transferred from a dedicated source that only delivers power without transmitting information to it such as directive power beam forming. The second method uses the same emitted RF signal to transport energy and information simultaneously, known as simultaneous wireless information and power transfer (SWIPT).

A number of receiver designs have been proposed for SWIPT. The two most adopted designs in literature are the integrated and the co-located receiver design. The co-located receiver design can be based on either time switching or power splitting. A power splitting block divides the received signal into two portions, one for EH and the other for information decoding, while time switching allocates dedicated time slots to EH and the rest for data processing. By employing this approach, controllable and efficient on-demand wireless information and energy can be simultaneously provided. This permits a low-cost alternative for sustainable wireless systems without further hardware modification on the transmitter side.

B. RF powered Cognitive Radio Networks

Powering a cognitive radio network (CRN) with RF energy can provide a spectrum- and energy-efficient solution for wireless networking. The idea of utilizing RF signals from primary transmitters to power secondary devices has been first proposed in [6]. In an RF-powered CRN, the RF energy harvesting capability allows secondary users to har vest and store energy from nearby transmissions of primary users . Then, the secondary users can transmit data when they are sufficiently far away from primary users or when the nearby primary users are idle. Therefore, the secondary user must n ot only identify spectrum holes for opportunistic data transmission but also search for occupied spectrum band/channel to harvest RF energy.

C. Non RF Energy Harvesting

The non RF Energy harvesting is in which the non RF signals such as solar, wind, temperature etc. are used for sensing the spectrum and data transmission purpose. It harvests from non-RF signal during sensing time of its detection cycle, and from both the sources, RF signal and non-RF signal, during transmission time as per sensing decision.

III. System model of Energy Harvesting based Cognitive Radio network

Before proceeding to the trade-off between maximizing harvested energy and optimizing SU throughput, the utilized configurations of SU and PU in EH-CRN, which are presented in Figure-2, are explained[7].

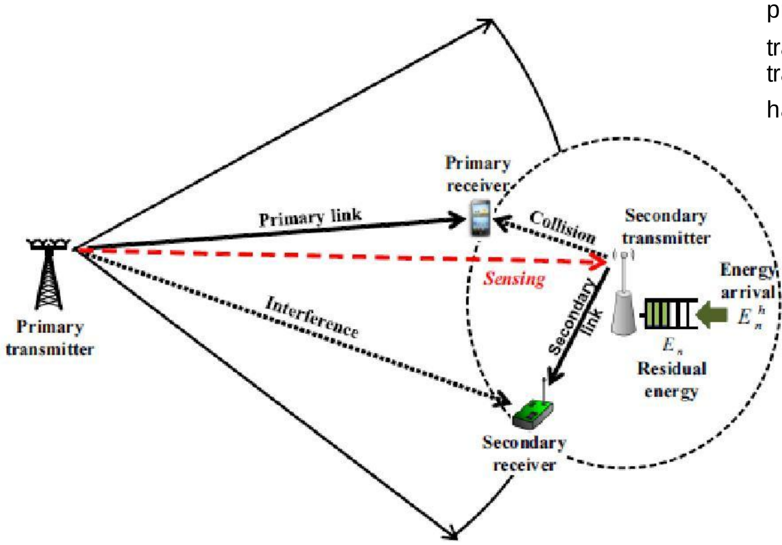

Fig. 2: A general system model of Energy harvesting based CRNs

A. Primary User Network

In [8], the PU network is assumed to consist of N channels where each channel bandwidth is W_n. The occupancy of PU bandwidth is considered a discrete time Markov process with 2^N states. For each time slot with duration $_s$lot, the state of PU channels randomly varies between 1 and 0 depends on discrete Markov process as follows,

C_n 2 f0(occupied); 1(idle)g

Where C is channel occupancy state and the spectrum switches between 1 and 0.

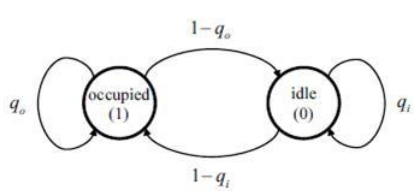

Fig. 3: The state of PU network transition

B. Secondary User Network

In [8] and [9], the SU transmitter is powered using finite capacity energy harvester B, as shown in figure 3. This harvested energy $E_h(t)$ is stored in battery in order to utilize it for SU sensing and transmission operations. The energy arrival at the harvested queue is assumed Bernoulli random variables. However, the energy arrival is assumed as inde-pendent and identically distributed (i.i.d.) sequence of random variables while in [8] is assumed to be stationary ergodic and independent of PU channel state. In [9], two assumptions are addressed. First is SU always has data to transmit. Second is SU synchronizes its operations with PU time slot in order to switch between two modes i.e. a_t 2 0(sleep); 1(active). As presented in figure 4, which indicates the operations of SU transmitter during only one PU channel, when $a_t = 0$, SU transmitter turns off all its operations except the energy harvester. The consumed energy in this case is e_i.

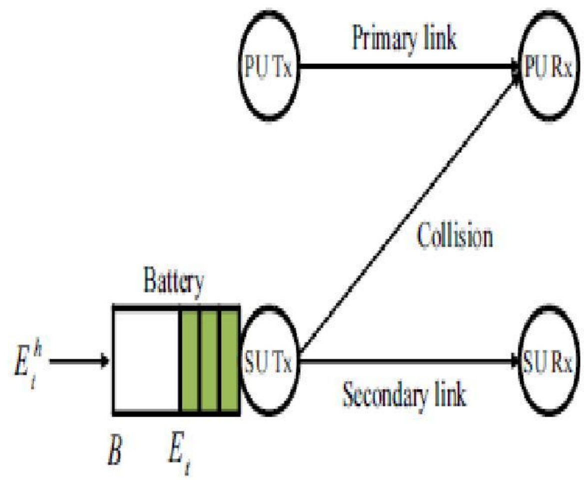

Fig. 4: Energy harvesting SU transmitter

IV. Throughput Maximization in Energy Harvesting

One of the key challenges in EN-CRN is maximizing SU throughput. Unlike to the conventional CRN where SU might be connected to the power source as well as the whole slot time for sensing idle channel then transmitting, in EN-CRN, the time slot is divided among harvesting, sensing and transmitting data. This policy of dividing the time slot is effecting on SU throughput. As the sensing duration increases, the accuracy of detection also increases. However, increasing sensing du-ration, results in decreasing throughput of data transmission. Therefore, next sections are reviewing this challenge in the contemporary research works.

A. Throughput Maximization using Detection Threshold

The performance of detecting the existence of primary signals is linked to the chosen value of the detection threshold. The choice of this value becomes even more crucial when the SU is an EH node [10]. the authors propose a technique by which an optimal detection threshold is derived, using the probability of accessing the idle spectrum and the probability of accessing the occupied spectrum to maximize the expected total throughput while satisfying both the EH and the collision constraints. They have also demonstrated that, depending on the selected threshold, the system can be characterized as a spectrum-limited regime and an energy-limited regime.

B. Throughput Maximization based on Primary User Signal

The CR user senses the presence of PU in time slotted model as shown in Fig.5 . It is considered that the CR detects (may be correctly or wrongly) the presence of PU in (N 1) consecutive frames when it only harvests energy without attempting to transmit while in the Nth frame it is able to transmit as the decision is in favour of the absence of PU. Each time frame (F_i) of CR consists of sensing time ($_i$) and transmission time (T_r; i) where i = 1; 2; 3 N. All the frames are of equal length, i.e., T_f = + T_r, and consists of the same sensing time (= $_1$ = $_2$ = = $_N$) and transmission time (T_r = $T_{r;1}$ = $T_{r;2}$::: = $T_{r;N}$). The CR senses the presence of PU and harvests RF energy during the sensing time. The CR keeps the energy splitting device switched ON during only [11].

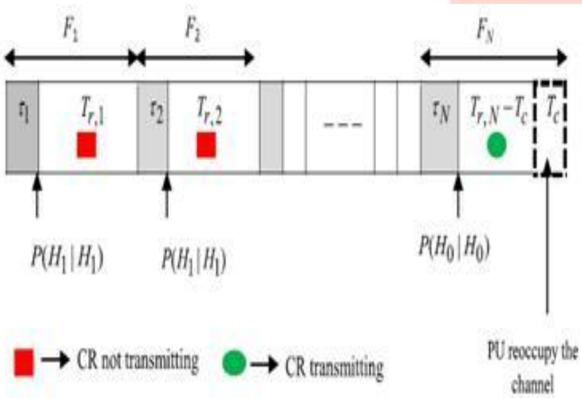

Fig. 5: Frame structure of detection cycles.

The performance of an energy harvested CR network is investigated in terms of harvested energy, outage probability and throughput with respect to several parameters such as sensing time, collision probability and number of frames.An optimal sensing time which maximizes the harvested energy has been estimated. There is also an optimal sensing time for which the average throughput of the system is maximum. The outage probability at CR receiver decreases as CR transmission power increases. A CR may suffer from energy outage if the transmission power increases beyond a certain level. The aver-age throughput is found to degrade as the collision probability increases while it improves with increase in number of frames.

V. Conclusion

The recent interest in simultaneously achieving spectrum and energy efficiency has led to the concept of RF-powered CRNs. This article presented an overview of the architecture of CRNs that operate based on RF energy harvesting. Mainly, two methods by which CRNs can harvest RF energy were discussed: intended and non-intended RF energy harvesting. Herein, the architectures and models for primary and secondary users as well as the channel models are presented. The main focus of this survey is investigating secondary user (SU).

Throughput. Finally, this topic of EH-CRN is a new topic thus it still face enormous challenges.

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