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Optimization of relay selection and ergodic capacity in cognitive radio sensor networks with wireless energy harvesting

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ABSTRACT

This paper addresses relay selection and resource allocation issues in cognitive radio sensor networks with wireless energy harvesting. We first consider a three-phase energy harvesting and information transmission protocol based on cooperative decode-and-forward relaying for a secondary system in coexistence with the primary system. In the first phase, the energy-constrained relay harvests energy through radio-frequency signals from the primary source. In the second phase, the destinations decode the primary signal. The relay uses the harvested energy to forward the primary signal and the secondary signal in the third phase. We derive the close-form upper bound of the ergodic capacity of the primary system and propose a relay selection algorithm. In particular, we calculate the critical region to ensure that the ergodic capacity of the primary system is equal or larger than that of the direct system. Finally, numerical results show that the proposed schemes achieve a satisfying performance.

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1. Introduction

With the explosive development of Internet of Things (IoTs), the further integration of various wireless communication networks comes into a ubiquitous network. The low-power wireless sensor networks (WSNs), one of the core components in perception layer of IoTs, have been adopted in large scale applications, such as personal health caring, traffic controlling and surveillance. Most WSNs employ the license-exempt industrial, scientific, and medical (ISM) spectrum [1]. However, with the wide application of Wi-Fi, ZigBee and Bluetooth, the mutual interference and coexistence problems of each communication system have become increasingly severe, which seriously restricts the future development of WSNs. Thus, the cognitive radio (CR) technology has been introduced to exploit more channel access opportunity in WSNs, that is, cognitive radio sensor networks (CRSNs).

With channel sensing and channel switching ability, a CR sensor node can access channel holes that are licensed to primary users (PUs) but not used by them, or work under the same licensed spectrum without affecting the PUs [2]. So the performance of CRSN can be largely improved by enhancing the spectrum efficiency. Nonetheless, these gains are at the cost of complexity and energy consumption of the secondary sensor node, which leads the low-power CR sensor node into a more energy-weaken state. Once the sensor nodes run out of battery energy, the network topology is changed and even the communication is interrupted.

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In order to overcome this problem, researches about extending network lifetime and improving the energy efficiency have been done. For the channel sensing stage, [3] studied an energy efficiency spectrum sensing technique for the cluster-based co-operative network architecture, and [4] minimized energy consumption by choosing the sleeping period and censoring parameters. For the data transmission stage, [5,6] proposed a time division multiplex access (TDMA) reporting frame structure and investigate a sensing-throughput tradeoff problem in cluster-based cooperative CRSNs. [7] saved the energy by joint subcarrier selection and power allocation in OFDMA system. [8] optimized the packet size energy-efficiently. Combining all CR-inherent operations, [9] proposed an energy efficiency channel management scheme, which allows the secondary user to adaptively select its mode among channel sensing, channel switching and data transmission/reception.

However, all these above strategies can only prolong the lifetime of CRSN to a certain extent. While replacing the batteries continuously can keep the CRSN active, it usually costs too much or even be hazardous in the case that the sensors are used for monitoring toxic substances. Recently, harvesting energy from the ubiquitous natural sources has been considered as a potential approach to prolong the lifetime of energy-limited CRSNs. Compared with the conventional uncontrollable sources, such as solar and wind, radio-frequency (RF) signals can be emitted manmade and thus not subjected to the unstable environment. The ambient RF radiation can be captured by the receiver antennas and converted into a direct current (DC) voltage through appropriate circuits (rectennas) [10]. The WSNs with RF energy transfer have been studied in [11–13]. More importantly, the distinct advantage of RF signals for energy harvesting lies in that RF signals can also carry data information. Therefore, the energy-limited sensor nodes can simultaneously harvest energy and decode information.

Varshney [14] first proposed simultaneous wireless information and power transfer (SWIPT) and analyzed the rate-energy (R-E) region from the perspective of information theory. In that work, Varshney assumed that the same RF signal can be double used for energy harvesting (EH) and information decoding (ID). Unfortunately, this ideal case cannot be achieved yet due to the limitation of hardware circuits. Thus, [15] proposed two more practical receiver schemes, i.e., time switching (TS) and power splitting (PS). TS means that the receiver switches between ID and EH modes, while PS represents that the receiver splits the received signal in two parts with one for ID and the other for EH. Since TS scheme can be implemented more easily in practice compared with PS, TS scheme is adopted in this paper.

Building upon these two practical receiver schemes, many research works on SWIPT have been done, including the rate-energy trade-off under single-input single-output (SISO) [16], multiple-input single-output (MISO) [17], multiple-input multiple-output (MIMO) [18] case and so on. Another interesting scenario is wireless cooperative relaying communications. [19] investigated the joint source and relay precoding strategy in a two-hop MIMO relay system under the assumption that the relay node has enough energy supply while the energy harvesting operation occurs at destination node.

Yet, the majority of the current research in relay-assisted networks has considered the scenario where the energy-constrained relay node needs to first harvest energy through the received RF signals from the source node and then uses the harvested energy to forward the source information to the destination node. Adopting the amplify-and-forward (AF) relaying scheme, [20,21] derived the analytical expressions for the outage probability and the ergodic capacity of relay networks; the achievable throughput performance of AF is also studied in [22]. Here, throughput represents the instantaneous capacity and ergodic capacity refers to the long-term average capacity. For the case of decode-and-forward (DF) scheme, the achievable throughput performance is considered in [22,23]. The power allocation strategies and outage performance under energy harvesting constraints are studied in [24]. Contrasting to [23] and [24], [22] allows energy accumulation at the relay node.

For the cognitive relaying networks without EH, [25] proposed a scenario where the secondary user helps to forward primary user's information in return for accessing the licensed spectrum. This cooperation is beneficial for secondary system to transmit its own data, as well as for primary system to meet its date requirement at lower power consumption. When it comes to CRSN, although the channel state between primary transmitter and secondary transmitter is good enough for the cooperation, the win–win situation would be broken by the secondary sensor node due to the lack of energy. This motivates us to introduce the RF energy harvesting to the cooperative relaying CRSN and thus provide cooperation both in information and energy level, through which the energy-limited secondary sensor node can keep working.

In this paper, we consider an RF–EH cooperative relaying CRSN scenario where the energy-limited secondary sensor nodes harvest the energy through RF signals broadcasted by the primary source and use the harvested energy to relay primary users' or their own information. Different from [26] which focused on the secondary user's beamforming strategy, we analyze the ergodic capacity of both the primary and secondary systems. Since the cooperation is incented by good cooperation condition (i.e., the channel state between primary transmitter and secondary transmitter), which enables secondary sensor nodes to decode the data correctly. Therefore, we assume that the secondary sensors help to relay primary users information based on the DF scheme. For the convenience of implementation, the TS protocol is adopted in the system. Consequently, we study the analytic expression of CRSNs' ergodic capacity after ensuring primary users performance.

The main contributions of this work are summarized as follows:

(1) We propose a three-phase energy harvesting and information transmission protocol in the energy-limited CRSNs.
(2) An optimal relay selection (RS) algorithm is proposed to maximize the ergodic throughput of the primary user. And the numerical results show that the proposed algorithm achieves a satisfying performance compared with the random RS.
(3) The ergodic throughput of the primary system as well as the secondary system are derived. Moreover, the critical region is derived to ensure that the ergodic throughput of the primary system is equal or larger than that without the secondary system.

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