Wirelessly Powered Cognitive Radio Communication Networks

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Abstract —Many energy harvesting techniques have been investigated in the literature to solve the limitation of power supply problems as it has been one of the crucial challenges in wireless communication networks. With the relatively large numbers of sensors that are expected to be deployed in the upcoming Fifth Generation (5G) and Internet-of-Things (IoT), it has become harder to implement reasonably priced networks with the normal power supplying techniques. In this paper, a proposal of a Cognitive Radio Network (CRN) is presented where the SUs have the ability of Secondary-Users (SUs) to wirelessly harvest energy from a broadcasted energy which is sent from a Central Node (CN). Additionally, the nodes that might not get sufficient energy from the CN are considered and solved by letting other near nodes relay some of the harvested energy to those do not get sufficient energy from the initial broadcast. This maintains a fair distribution of energy among all the cognitive radio nodes in the network. The individual and overall network throughput is derived and investigated as well in order to validate the amount of transmitted data in the network.

Index Terms—CRN, wireless powered devices, broadcasted power, energy harvesting, cooperative CRN, wireless powered communication systems.

I. Introduction

Deployment of wireless networks has been gaining a lot of attention over the past decade as it is considered the main building block for the Internet-of-things (IoT) and the fifth cellular generation (5G). In order to enable IoT technology, research has been contributing a lot in developing many technologies such as the Wireless Sensor Networks (WSNs), Energy Harvesting (EH) approaches, and Cognitive Radio Networks (CRNs). WSNs have been proposed to be implemented in industries such as agriculture, healthcare, smart manufacturing, and underwater environmental applications. However, it is not ready yet to be implemented fully due to the scarcity of the spectrum and the power requirements of such numerous numbers of WSNs. Additionally, there are a lot of restrictions on the transmission and data processing in wireless networks due to the power constrains of these mostly battery operated nodes. This has made the concept of harvesting energy from multiple different sources the solution for such a problem. Mainly, wireless nodes can harvest energy from radio frequency (RF) signals, solar energy, vibrations energy, and many more. Energy harvesting (EH) is still considered an optimistic research direction in wireless networks. Thus, merging WSN, EH, and CRN has been discussed in the literature for application to such systems where it is not suitable to operate mainly on batteries and with the limitation of spectrum resources.

Two different techniques for wireless energy harvesting have been discussed in literature. Simultaneous wireless transfer of Information and Power (SWIPT), and wireless transmission of information in uplink (UL) and transfer of energy in the downlink (DL) [1]. The authors of [2] have proposed a novel approach of managing the harvested energy in a network with nodes equipped with energy harvesters for data transmission in wireless sensor networks. The work proposed here is similar to [1] but adding CR capabilities to the nodes. A Markovian model was used to investigate EH in CRN in [3, 4] but without considering the fairness problem of the far nodes. Authors of [5] proposed a system in which a charging vehicle will periodically enter the network and wirelessly charge the batteries of the nodes. However, This will add extra infrastructure to the network which may not be a good approach economically.

Cognitive Radio wireless sensor networks (CRWSNs) have been slowly merging with EH capabilities in order to achieve high Quality of Service (QoS). Several research papers have been working on enhancing the transmission delay and transmission of data. For example, the idea of combining CRWSNs and EH was tested in [6], where the SUs harvest energy from transmissions performed by the PU. But, since the PU transmissions may be sporadic from the point of view of the SUs, SU nodes may not get enough power from that source. Additionally, several approaches have been proposed to solve the Near-Far problem as in [1], [7]-[9]. Authors of [8] and [9] tested the effect of multiple antennas on solving this problem. On the other hand, the authors of [1] and [7] discussed an optimization problem of the time and power allocation in order to maximize the overall common throughput in a new approach instead of the summation of throughput of all nodes. Moreover, cooperation among users can be employed to solve the Near-far problem as well as in [10]-[13] with aim to improve the network throughput.

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This paper discusses wireless transmission of the information in the UL and energy in the DL. The network model is considered a centralized network model in which a central node (CN) broadcasts a high amount of power wirelessly in the DL to a set of uniformly distributed nodes with cognitive radio capabilities and radio frequency energy harvesters (RFEHs). While in the UL, the CRWSNs send their information to the central node in Time Division Multiple Access (TDMA) approach. The network model used in this paper avoids the Near-Far problem, where far CRWSNs may suffer from low harvested energy when compared to the near users. An effective solution to this problem is to assign some of the near CRWSNs the job of relaying some of the harvested energy to the far CRWSNs with the goal of achieving fairness, continuous connectivity, and maximum throughput of the network as a whole. The relay nodes employ amplify-and-forward scheme to avoid complex processing and high waste of the harvested energy. The rest of the paper is organized as follows; the network model is presented in Section II. Section III describes the results and discussion. Section IV concludes the paper.

II. Network Model

The model in this paper is inspired by [1] which discussed a similar model for wireless sensor nodes (WSNs). Our model considers a similar network but with adding cognitive radio capabilities to the nodes. The CRWSNs receive broadcasted energy in the DL from the central nodes (CN) and send their information in the UL. The network model is shown in Fig 1. It consists of one CN and K CRWSNs. The CN periodically broadcasts constant energy in all directions. The CRNs are equipped with only one antenna and their energy depends totally on the RF energy harvested from the broadcasted energy.

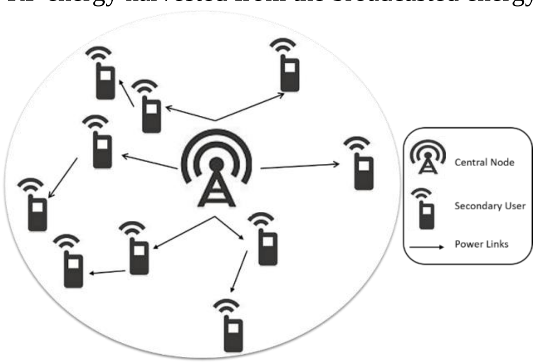

Fig. 1. Wireless powered cognitive radio network

The channel state information (CSI) and locations of the CRWSNs are assumed to be well known to the CN. Also, the network assumes a uniform distribution of the CRWSNs in a grid circle based network with radius r. Relay CRWSNs use amplify-and-forward scheme with negligible processing energy.

Fig. 2 shows the proposed time frame of each of the CRWSNs in a cooperative and non-cooperative sensing manner where the harvesting and sensing slots take only 10% each of the overall time frame. Harvesting slot is the time used during harvesting of the energy. However, the sensing slot is used for sensing vacant spectrum band.

The rest 80% of the time frame are used for self-data transmission and relayed energy for far nodes. on the other hand, nodes which are selected to work as relays either transmit their data during the total transmission time slot or use the time slot to both relay some of the energy and transmit their own data. This depends mainly on the availability of a transmission from the far Node.

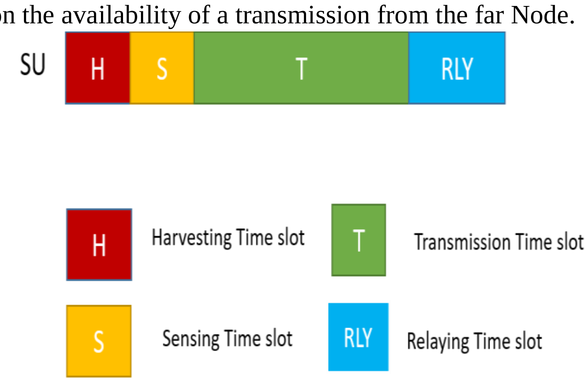

Fig. 2. Time frame of cooperative and non-cooperative users

At each CRWSN, the state of the spectrum can be described by H_0 and H_1, which represent the spectrum being either idle or occupied, respectively. Their steady state probabilities can be written as:

$$P(H_1) = \frac{1 - q_i}{2 - q_i - q_o} \tag{1}$$

$$P(H_o) = 1 - P(H_1) \tag{2}$$

The probability of spectrum states changes based on whether the primary user (PU) is transmitting or not. The spectrum state remain unchanged with probability q_o or it changes to idle state with probability $(1 - q_o)$ in the next time slot, if the spectrum is occupied by the PU. While, the spectrum remain idle with probability q_i or change to occupied state with probability $(1 - q_i)$ in the next time slot, if the spectrum is idle in the current slot. The received signal at any of the CRNs is:

$$y_i(n) = \begin{cases} w_i(n) \quad , & for\ H_0 \\ w_i(n) + s_i(n), & for\ H_1 \end{cases} \tag{3}$$

where $s_i(n)$ and $w_i(n)$ represent the primary and noise signals, respectively. Both values are modelled with a circularly symmetric complex Gaussian distribution (CSCG) with variances σ_s^2 and σ_w^2 respectively. CRWSNs detect the signal $\mathrm{T(y_i)}$ based on the calculation of their energy:

$$T(y_i) = \frac{1}{N} \sum_{n=1}^{N} |y_i(n)|^2 \tag{4}$$

The summation of the received signals in the energy detection is calculated with number of samples (N) of CRWSNs. where $N = \tau_s f_s$, and τ_s and f_s are the sensing time and sampling frequency, respectively.

For high probability detection of the transmission of CRWSNs, $P_d(\lambda)$ is maximized and probability of false alarm $P_f(\lambda)$ is at the minimal to avoid false sensing of the PU. The probabilities of false alarm and detection can be written as:

$$P_f(\lambda) = Q((\frac{\lambda}{\sigma_w{}^2} - 1)\sqrt{\tau_s f_s}\,) \tag{5}$$

$$P_d(\lambda) = Q(\left(\frac{\lambda}{(\gamma_p + 1)\sigma_w{}^2} - 1\right)\sqrt{\tau_s f_s}) \tag{6}$$

where γ_p is the measured Signal-to-noise-ratio (SNR) of the PU, λ is the received signal strength at CRWSNs, and $\sigma_w{}^2$ is the noise power. The individual achievable throughput is derived based on [1] as:

$$R_i = \left(1 - P_f(\lambda)\right) P(H_0)\ A\ log_2(1 + B\frac{T_o}{T_i}) \tag{7}$$

where $A = \tau_i$ and $B = \frac{P_o h_{io}{}^2}{\sigma^2}$ are used for direct mode. While $A = \tau_{ir}$ and $B = \frac{P_o h_{io} h_{ij} h_{jo}}{\sigma_w{}^2\,(h_{jo}+1)}$ are considered for the relayed mode. In both cases, P_o is the fixed broadcasted energy, h_{io}, h_{jo} , and h_{ij} are the channel gain between the source i and destination o, relay j and destination o, and source i and relay j, respectively.

The channel gain is measured as:

$$h_{ij} = 10^{-3}\rho_i{}^2 r_{ij}{}^{-\alpha}, \qquad i,j = 1,2,\ldots,K \tag{8}$$

where, α is the path loss exponent, ρ_i is the Rayleigh short-term fading, and r_{ij} is the distance between nodes i and j.

III. Simluation Results and Discussion

The proposed model is evaluated by testing it in two scenarios of cooperative and non-cooperative CRNs. The simulations are conducted under assumption that relaying function in the near CRWSN happens when the far CRWSNs do not have sufficient energy to transmit. While, direct transmission happens in case of far CRWSNs having sufficient energy for transmission. Both scenarios are considered in our results. The evaluation of the two scenarios is done using the simulation parameters listed in Table I.

TABLE I: Network Simulation Parameters

Parameter	Description	Value
K	Number of nodes	10
P_0	Power broadcast from CN	50-100 dBm
r	Radius of the circular area where nodes are located	100 m
P_d	Probability of detection	90%
q_o	Transition Probability of being occupied	0.7 [14]
q_i	Transition Probability of being idle	0.5 [14]
SNR	Signal-to-Noise-Ratio	-20-10 dB
τ_s	Sensing time	20 ms
f_s	Sampling frequency	1 MHz
T	Frame time	100 ms

Figs 3 and 4 show the individual normalized throughput according to the SNR, and Downlink power, respectively. Both Relaying and Direct Transmission of CRWSNs were tested. Direct transmission occurs when the CN does not assign a relay for a far CRWSN. This usually occurs when far CRWSNs have harvested sufficient energy for transmission and the network has a high traffic in the current state. This makes the CN decide to maintain the network throughput over fairness. Also, as the downlink power increases, the individual throughput is slightly increased in both cases. In general, CRNs who are located near the CN perform better than far CRWSNs. This is mainly because the path loss which is lower at the near nodes. Despite this loss, the network model maintains connectivity to CRWSNs that do not have sufficient power which helps to avoid loss of data.

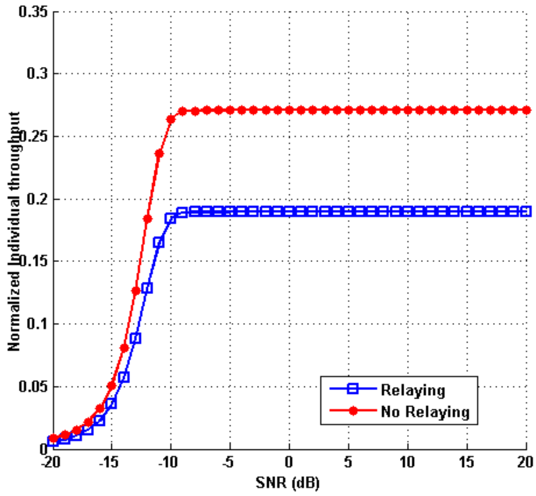

Fig. 3. Normalized achievable throughput vs SNR

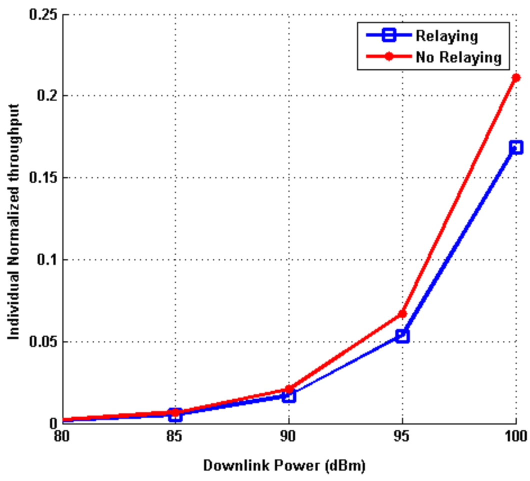

Fig. 4. Normalized achievable throughput vs Downlink power where SNR= -10dB

Additionally, we can observe that the achievable throughput in Figs 3 and 4 increases monotonically as the SNR increases and saturates at SNR=-10 dB. This happens because the probability of false alarm saturates. Also, direct transmission has a higher throughput than the relaying as the transmission time slot is reduced when the node is in relaying mode. Furthermore, it is apparent that the throughput decreases as well due to the increase in the channel gain of the relaying links. The network throughput is measured as 27%, and 19% for direct and relaying transmission, respectively.

Fig. 5 shows the overall network throughput in Mbps with respect to the SNR. In the case of Relaying, all CRWSNs are connected and able to transmit which makes the throughput reaches a value of about 13 Mbps at SNR=-10dB. While, without Relaying, 40% of the CRWSNs who can't harvest sufficient energy to transmit their own data are disabled which reduces the overall network throughput by around 1 Mbps. This value is because these far nodes contribute with a lower value to the overall throughput.

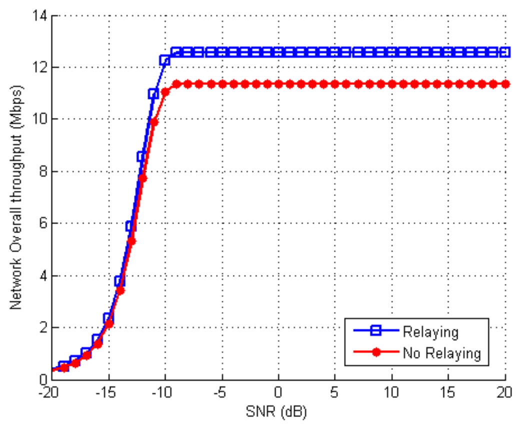

Fig. 5. Overall network throughput vs SNR

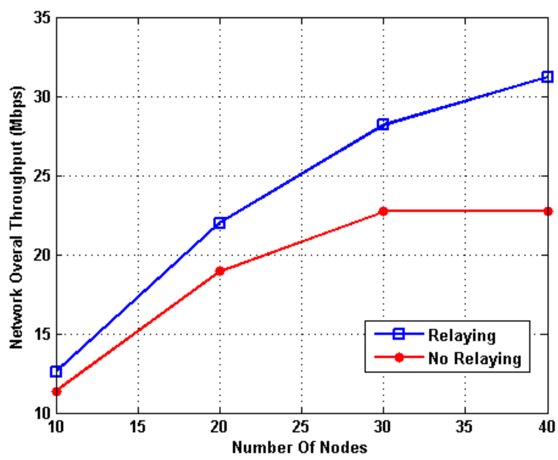

Fig. 6. Overall Network throughput vs Number of nodes

Additionally, the network model is tested the effect of the number of nodes in the network on the overall throughput. The results shown in Fig. 6 represent the overall network throughput with various network sizes where the network consists of 10, 20, 30, and 40 nodes.

Fig. 6 shows that the overall network throughput increases with the increase the number of nodes for both scenarios. But, in the relaying scenario, we can see from the figure that there is more increase in the overall throughput than that of the no-relaying scenario. This is because of the relaying, farther node are able to access the network which leads to an increase in the overall throughput.

Finally, the overall throughput in the no relaying scenario saturates when it the network has 30 or more nodes. This is because the number of the far nodes increases which means that more nodes will not be able to access the network which leads to higher loss which saturates the overall throughput at 23 Mbps. On the other hand, in the relaying scenario, we can observe that the overall network throughput monotonically increases until it reaches 32 Mbps in the case of 40 nodes.

IV. Conclusions

In this paper, we have proposed a cognitive radio network model in which, the cognitive radio nodes are able to wirelessly harvest energy from a broadcasted energy periodically sent from a central node. Moreover, we considered the nodes that might not get sufficient energy from the central node by letting near nodes relay some of the harvested energy to those who do not get sufficient energy. This is done to maintain fairness distribution of energy among all cognitive radio nodes. The individual throughput measurements have shown that transmission reaches 27% and 19% for direct and relay transmission, respectively. While, the overall network throughput reaches 13 and 11 Mbps for relay and direct transmission modes, respectively. Also, this Network model maintains connectivity to all CRWSNs including those who do not get sufficient energy from the CN. This enables about 40% of the CRWSNs to be connected. Additionally, the effect of the number of nodes in the network was investigated. The overall network throughput linearly increases until it reaches 32 Mbps at 40 nodes in the relaying scenario. While it only reaches 23 Mbps in the no relaying scenario and saturates. This is because the number of nodes which do not get sufficient energy for transmission increase as we add more nodes to the network.

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