Throughput Maximization for Underlay Cognitive Radio Networks with RF Energy Harvesting

He Xiao¹,², Hong Jiang¹ and Xiao-li He¹

ABSTRACT

This paper presents a green cognitive radio networks (CRNs) framework with radio frequency (RF) energy harvesting, namely RF-powered cognitive radio networks (RF-CRNs), where secondary users (SUs) first harvests energy from the RF signals of primary users and then transmits data using the harvested energy in one slot. The total consumed energy by the SU must be equal or less than the total harvested energy referred to as energy causality constraint, while the transmission power of SU must be restricted in order to protect the primary user from interference, namely collision constraint. Finally, under the satisfaction of quality-of-service (QoS) of SU (namely throughput constraint), our goal is to determine an optimal transmitting time and power allocation that maximizes its throughput in the RF-CRNs. We achieved the optimal result by transforming optimization problem into convex optimization and then applying Lagrange multiplier methods. Extensive performance evaluations conducted show the efficiency of the proposed algorithm.

Key words: Cognitive radio, Energy harvesting, Underlay, Energy causality, Throughput constraint

1. INTRODUCTION

The cognitive radio networks with energy harvesting (EH-CRNs) have emerged as a promising way to address the problem of spectrum scarcity and energy efficiency while consistent with the call for green communication at the same time [1-3]. RF energy harvesting technique allows a wireless node to harvest and convert electromagnetic waves from ambient RF sources (e.g., TV, radio towers and cellular base stations) into energy which can be used for data transmission. Comparing with ambient energy harvesting such as heat, light and wave, the RF energy harvesting is more flexible and sustainable because the RF signals radiated by ambient transmitters are consistently available [4-5].

RF energy sources can mainly be categorized into dedicated RF and ambient RF. Dedicated RF can power the nodes which require predictable energy due to on-demand supply and directional transmission, such as wire powered communication networks (WPCNs) in which distributed wireless devices are powered via dedicated wire energy transfer (WET) by the hybrid access point in the downlink for uplink wireless information transmission [6-8], simultaneous wireless information and power transfer networks (SWIPT)

¹He Xiao, Hong Jiang, Xiao-li He, Southwest University of Science and Technology, Mianyang, China
²He Xiao, China West Normal University, Nanchong, China
in which the information and energy are included in the RF signals at the same time [9-11]. Ambient RF signals concludes most of the radiations from nearby RF sources such as base stations, primary licensed networks and other secondary sources. It is freely available and not dedicated for energy harvesting, mainly power for low-power networks, such as sensor networks [12-15].

In this paper, we consider an underlay ambient RF-CRNs in which the battery-free SU first harvests energy from the RF signal of PU and then transmit data using the harvested energy. Under the energy causality constraint as well as interference constraint, our goal is to achieve the maximum of throughput in the RF-CRN while guarantee the transit QoS of SU.

2. SYSTEM MODEL

As shown in Figure 1, we consider a time-slotted RF-CRN with one PU transmitter (PT)-PU receiver (PR) pair and one SU transmitter (ST)-SU receiver (SR) pair. The link between the PT and ST is referred as energy harvesting links. The links between PT (ST) and SR (PR) are referred as interference links. The links between PT (ST) and PR (SR) are referred as the data transmission links. We assume all the channels remain constant during each slot, but may change from one slot to another.

The SR has a fixed power supply, whereas ST is self-powered by harvesting energy from RF signals of the PT. To reduce the complexity of hardware design, we let ST operates in half-duplex mode, i.e., it can only harvest energy or transmit data at one time. We consider a frame with duration $T$ which is slotted and allocated to ST for harvesting and transmission as shown in Figure 2.

A. Energy harvesting phase

We assume that at the beginning of the slot the initial energy of the ST is zero for convenience. After harvesting energy for a duration $\tau_0$, the energy achieved for ST by the end of this phase is calculated as

$$E_H = \eta G_e P_T \tau_0$$

(1)
where $\eta$ represents the EH efficiency, $g_e$ is channel power coefficients and $P_T$ is the transmitting power of PT.

**B. Transmitting phase**

In this phase, the ST consumes the harvested energy to transmit data. Obviously, the total consumed energy of ST must be equal or less than the total harvested energy in the EH phase, namely energy causality constraint.

$$ (P + P_e) \tau \leq E_H $$ (2)

where $P$ is the transmitting power of ST, $P_e$ is the circuit energy consumption accounting for ST. $g_s$ is channel power coefficients.

The ST shares the spectrum with the PU in an underlay paradigm, so the transmitting power of ST must be restricted in order to protect the primary user from interference, namely interference collision constraint.

$$ P_{g_sp} \leq P_I $$ (3)

where $P_I$ is the peak permissible interference threshold for PR. We calculate the achievable throughput of SU in one frame as follows:

$$ R(\tau, P) = \tau \log_2 (1 + \frac{P_g}{P_I g_{ps} + \sigma^2}) $$ (4)

Where $g_{ps}$ is channel power coefficients, $\sigma^2$ denotes the noise power at the SR. Comparing best-effort communication network, in order to satisfy QoS of SU, we set a minimum required rate $R_{out} > 0$ for SU, namely throughput constraint,

$$ R(\tau, P) \geq R_{out} $$ (5)

**C. Problem Formulation**

Combining (2)-(5) we formulate the throughput maximization problem for the RF-CRNs as follows,

$$ \text{OP1: max } R(\tau, \tau, P) = \max \tau \log_2 (1 + \frac{P_g}{P_I g_{ps} + \sigma^2}) $$

$$ \text{C1: } (P + P)e \tau \leq \eta g_e P_I \tau_b $$

$$ \text{C2: } P g_{sw} \leq P $$

$$ \text{C3: } R(\tau, P) \geq R_{out} $$

$$ \text{C4: } 0 < \tau < T $$

$$ \text{C5: } 0 < P \leq P_{max} $$ (6)

In C1, under the allocated time and transmission power, the consumed energy for data transmission can’t exceed the harvested energy. C2 indicates that the transmission power of ST can’t exceed the tolerable inference power threshold at the PR, through which the PR is protected from interference. C3 is the throughput constraint. C4 indicates that the total time consumed by must equal to or less than a frame duration. Lastly, C5 is the transmitting power.
maximization constraint for ST.

3. SOLUTION METHOD

The throughput is obviously monotone increasing with respect to $\tau$. Thus, we can always find $\tau'$ ($\tau' > \tau$) that satisfying $R(\tau_0, \tau', P) > R(\tau_0, \tau, P)$, so the maximal throughput $R(\tau, P)$ for OP1 is always achieved at $\tau_0 + \tau = T$. According to Lemma 1, we can transform the OP1 into a simplified form OP2 by eliminating $\tau_0$.

$$\text{OP2: max } R(\tau, P) = \frac{g_i}{P_r g_m + \sigma^2}$$

$$\begin{align*}
C1: & (P + P_r) \tau \leq \eta g_e P_i (T - \tau) \\
C2: & P_{op} \leq P_i \\
\text{s.t.:} & C3: R(\tau, P) \geq R_{out} \\
& C4: 0 < \tau < T \\
& C5: 0 < P \leq P_{\text{max}}
\end{align*}$$

(7)

The problem OP2 is non-convex due to there is the product of the optimal variable $P$ and $\tau$ in C1. To make OP1 tractable, we introduce new optimization variables $e = P\tau$ and transform the OP2 into the following form with respect to $\tau$ and $e$, where $e = \frac{\gamma g_i}{P_r g_m + \sigma^2}$ is defined for convenience.

$$\text{OP3: max } R(\tau, e) = \frac{\log_2(1 + \frac{e}{\tau})}{\tau}$$

$$\begin{align*}
C1': & e \leq \eta g_e P_i (T - \tau) - P_c \tau \\
C2': & e g_{op} \leq \tau P_i \\
C3': & R(\tau, e) \geq R_{out} \\
C4': & 0 < \tau < T
\end{align*}$$

(8)

The achievable throughput $R(\tau, e)$ is a jointly concave function of $\tau$ and $e$. After introducing $e$, the energy causality constraint C1 is converted into an affine function as C1'. Thus, OP3 is a convex optimization problem that can be solved by the convex optimization techniques.

We firstly introduce the partial Lagrangian function of OP3 with respect to $C1'$, $C2'$, $C3'$.

$$L(\tau, e, \lambda, u, v) = \frac{\log_2(1 + \frac{e}{\tau})}{\tau} - \lambda (e - \eta g_e P_i (T - \tau) + P_c \tau)$$

$$- u (e g_{op} - \tau P_i) + v (R_{out} - R(\tau, e))$$

(9)

As problem OP3 is a convex optimization problem, there is strong duality between the primal and dual problem by Slater’s condition.
\[
\begin{align*}
\frac{\partial D}{\partial \lambda} &= -(e - \eta g, P_e (T - \tau) + P_e \tau) \\
\frac{\partial D}{\partial u} &= -(eg_p - \tau P) \\
\frac{\partial D}{\partial v} &= R_{nre} - R(\tau, e) \\
\end{align*}
\]

(10)

According to the KKT condition, the optimal solution must satisfy \(\frac{\partial L(e, u, \lambda, v)}{\partial \tau} \bigg|_{\tau=0} = 0\) and \(\frac{\partial L(e, u, \lambda, w)}{\partial e} \bigg|_{e=0} = 0\). We get the \(\tau^*\) and \(e^*\). Next, we compute the optimal dual variables the optimal \(\lambda, u, v\) that minimize \(D(\lambda, u, v)\) by using the sub-gradient method. The sub-gradients of \(D(\lambda, u, v)\) at \(\lambda, u\) and \(v\) are calculated as equation (10). And in the n-th iteration, we update \(\lambda, u, v\) as follows

\[
\begin{align*}
\lambda^{(n)} &= \max \left\{ 0, \lambda^{(n-1)} + \alpha^{(n-1)} \left( \frac{\partial D}{\partial \lambda} \right)^{(n-1)} \right\} \\
u^{(n)} &= \max \left\{ 0, u^{(n-1)} + \alpha^{(n-1)} \left( \frac{\partial D}{\partial u} \right)^{(n-1)} \right\} \\
v^{(n)} &= \max \left\{ 0, v^{(n-1)} + \alpha^{(n-1)} \left( \frac{\partial D}{\partial v} \right)^{(n-1)} \right\} \\
\end{align*}
\]

(11)

Where \(\alpha^{(n-1)}\) denotes the step-size in the n-th iteration.

4. SIMULATION AND RESULTS

In this subsection, we present simulation results to indicate the effective performance of the proposed scheme. All network parameters are selected to describe typical RF-CRNs. Specifically, we set the parameters as follows: the energy harvesting efficiency \(\eta = 0.7\), the duration of time slot \(T = 1\), the energy harvesting link gain \(g_e = 0.9\), the primary interference link gain \(g_{ps} = 0.3\), the secondary interference link gain \(g_{sp} = 0.2\), the secondary transmission link gains \(g_s = 0.9\), the noise power \(\sigma^2 = -65dBm\), the circuit power \(P_c = 0.02W\) and the maximum transmission power of ST is \(6W\). From Figure 3, we can observe that throughput achieves a maximum when \(\tau = 0.53\) and \(P = 6W\).
From Figure 4, it is obviously that the throughput increases with the increase of the $P_T$, which due to the fact that the increasing $P_T$ enlarges the feasible domain of the ST transmission power $P$ and further increasing $R(\tau, P)$. At the same time, $R(\tau, P)$ is also decreasing with increasing of $P_T$. Larger $P_T$ is meaning more harvested energy for SUs, but also more interference to the SR. So, when the interference is large enough or the $P_T$ is tight, the SU can’t satisfy the prescribed minimum throughput threshold, the throughput dramatically decreases to near zero and the system interrupted.

Figure 5 demonstrates the relation between the throughput $R(\tau, P)$ and $P_T$. As describing in Figure 4, with $P$ enlarging as the increasing of $P_T$, $R(\tau, P)$ and the consumed energy is increasing accordingly. However, when $P_T$ is sufficiently large, $R(\tau, P)$ can’t be further enhanced. In fact, $P$ can’t be unlimited due to the finite harvested energy and the max power transmission constraint $P_{\text{max}}$.

5. CONCLUSIONS

We solve the maximization problem of throughput maximization for underlay RF-CRNs in this paper. The RF signals radiated by the primary users are no longer interference for the second users, but can be regarded as green energy sources for energy harvesting. In this way, SUs can utilize both the spectrum and the energy of primary users. Through the throughput constraint, we ensured transmission QoS for second users, which is essential in many
applications especially in wireless sensor network performing data gathering, event monitoring and other industrial applications. Lastly, we achieved the optimal result by transforming optimization problem into convex optimization and then applying Lagrange multiplier methods. Through the maximization of harvesting energy and the minimum throughput constraint, our model can be expanded easily and applied to many important occasions such as large scale cognitive radio networks, cognitive relay networks and multi-hop cognitive radio networks.

Acknowledgement

This work was supported in part by the National Natural Science Foundation of China under Grant No. 61771410, and in part by the Scientific Research Fund of Sichuan Provincial Education Department under Grant. NO 16ZB0185 and in part by Postgraduate Innovation Fund Project by Southwest University of Science and Technology (Grant. NO 18ycx115).

REFERENCES

1. Park S, Hong D. Achievable Throughput of Energy Harvesting Cognitive Radio Networks [J]. IEEE Transactions on Wireless Communications, 2014, 13(2):1010-1022.
2. Mohjazi L, Dianati M, Karagiannidis G K, et al. RF-powered cognitive radio networks: technical challenges and limitations [J]. Communications Magazine IEEE, 2015, 53(4):94-100.
3. Lu X, Wang P, Niyato D, et al. Wireless Networks With RF Energy Harvesting: A Contemporary Survey [J]. IEEE Communications Surveys & Tutorials, 2015, 17(2):757-789.
4. Feng Daquan, Jiang Chenzi, Lim Gubong, et al, A survey of energy-efficient wireless communications[J], IEEE Communication Surveys & Tutorials, 2015, 17(2):167-178.
5. D. T. Hoang, D. Niyato, P. Wang, and I. K. Dong. " Opportunistic Channel Access and RF Energy Harvesting in Cognitive Radio Networks," IEEE Journal on Selected Areas in Communications, vol. 32, pp. 2039-2052, Nov. 2014.
6. Ju H, Zhang R. Throughput Maximization in Wireless Powered Communication Networks [J]. IEEE Transactions on Wireless Communications, 2014, 13(1):418-428.
7. Chen H, Li Y, Rebelatto J L, et al. Harvest-Then-Cooperate: Wireless-Powered Cooperative Communications [J]. IEEE Transactions on Signal Processing, 2015, 63(7):1700-1711.
8. Yao Q, Huang A, Shan H, et al. Delay-Aware Wireless Powered Communication Networks—Energy Balancing and Optimization [J]. IEEE Transactions on Wireless Communications, 2016, 15(8):5272-5286.
9. J. Xu, L. Liu, and R. Zhang, “Multiuser MISO beamforming for simultaneous wireless information and power transfer,” IEEE Trans. Signal Process., vol. 62, no. 18, pp. 4798–4810, Sep. 2014.
10. S. Lee, L. Liu, and R. Zhang, “Collaborative wireless energy and information transfer in interference channel,” IEEE Trans. Wireless Commun., vol. 14, no. 1, pp. 545–557, Jan. 2015.
11. Z. Ding, I. Krikidis, B. Sharif, and H. V. Poor, “Wireless information and power transfer in cooperative networks with spatially random relays,” IEEE Trans. Wireless Commun., vol. 13, no. 8, pp. 4440–4453, Aug. 2014.
12. Yin S, Qu Z, Li S. Achievable Throughput Optimization in Energy Harvesting Cognitive Radio Systems [J]. IEEE Journal on Selected Areas in Communications, 2015, 33(3):407-422
13. Hoang D T, Niyato D, Wang P, et al. Performance Optimization for Cooperative Multiuser Cognitive Radio Networks with RF Energy Harvesting Capability[J]. IEEE Transactions on Wireless Communications, 2015, 14(7):3614-3629
14. Meng Z, Wei L, Yu H. Harvesting-Throughtput Tradeoff for CDMA-Based Underlay Cognitive Radio Networks with Wireless Energy Harvesting [J]. Electronics Letters, 2016, 52(10):881-883.
15. Yun H B, Baek J W. Achievable Throughput Analysis of Opportunistic Spectrum Access in Cognitive Radio Networks with Energy Harvesting [J]. IEEE Transactions on Communications, 2016, 64(4):1399-1410
16. S. Boyd and L. Vandenberghe, Convex Optimization [M]. Cambridge, U.K.: Cambridge Univ. Press, 2004.