Optimal Energy Harvesting Time and Power Allocation Policy in CRN Under Security Constraints from Eavesdroppers

Hung Tran*, Truong Xuan Quach †§, Ha-Vu Tran‡, and Elisabeth Uhlemann*

*Mälardalen University, Västerås, Sweden

†VNU University Engineering and Technology, Vietnam

‡University of Québec, ETS Engineering School, LACIME Laboratory, Montreal, Canada

§TNU - University of Information and Communication Technology, Vietnam.

Email: *{tran.hung, elisabeth.uhlemann}@mdh.se, †qxtruong@ictu.edu.vn, ‡ha-vu.tran.1@ens.etsmtl.ca

***Abstract*—In this paper, we study energy harvesting cognitive radio networks (CRNs) in the presence of multiple eavesdroppers (EAVs) and multiple primary users (PUs). In particular, the secondary user (SU) harvests energy from multiple primary user transmitters (P-Tx), and then uses this harvested energy to deliver packets to the secondary access point (SAP). The SU communication faces multiple EAVs intending to steal its confidential information. In order to protect itself against multiple EAVs and also to protect the PUs communication from interference generated by the SU signals, the SU should be equipped with a suitable power allocation strategy which is derived from channel state information, harvested energy, security constraints given by the SU, and interference constraint given by the PU. Accordingly, an energy harvesting and communication protocol is proposed. Further, the optimal energy harvesting time, a power allocation policy, and a channel selection strategy for the SU are derived and analyzed. To this end, closed-form expressions for the packet error probability and the average packet delay including retransmissions are obtained. Interestingly, the numerical results obtained in this paper show that the proposed power allocation and channel selection strategy does not only improve the spectrum and energy utilization, but also protect the confidential information of the SU from the EAVs.**

***Index Terms*—Energy Harvesting, Power Allocation, Cognitive Radio Networks, Physical Layer Security.**

I. INTRODUCTION

Recently, energy harvesting from ambient sources, e.g. solar and wind, has been considered as a promising technique that can help to overcome the energy constraints of wireless networks. Therein, radio frequency (RF) energy harvesting is especially interesting due to its flexible and sustainable characteristics in the areas where wireless transmitters are deployed densely, and their RF signals are consistently available [1]. These sources can provide enough energy for wireless sensor networks in which the power demand for sensor nodes is low [2]. For networks requiring more energy, sophisticated wireless power transfer techniques have been designed [3]–[5].

When energy harvesting is studied in cognitive radio networks (CRNs), the RF signals generated by the primary transmitter (P-Tx), which is traditionally considered as harmful interference to the secondary user (SU), can instead be converted into useful energy for SU communications. Accordingly, the SUs can utilize both the licensed spectrum and the energy belonging to the primary user (PU).

In energy harvesting CRN, two major paradigms have been proposed to exploit the energy and the licensed spectrum of the PU, namely interweave and underlay. In the interweave approach, the SU first harvests energy from active PUs and then opportunistically access the licensed spectrum as long as it is not occupied by the PU. In [6], Chung *et al.* have proposed a solution to not only optimize the spectrum sensing process, but also maximize the throughput of the SU when it scavenges energy from ambient sources. In [7], a novel spectrum access approach has been proposed to maximize the throughput for the CRN, where the SU utilizes the energy radiated from the active PUs. In [8], authors have investigated a scenario where SUs opportunistically scavenge energy from the nearby PUs, then outage probability and throughput have been derived. In the underlay paradigm, the SUs use the harvested energy to transmit packets as long as the interference at the PUs is kept below a tolerable threshold. In [9], an optimal time allocation between the energy harvesting and information transmission phases has been investigated in an underlay CRN, and the average achievable rate has been optimized under the outage constraint of PUs. Outage probability has been derived for two system models in [10], [11] where the SU can harvest either from the SUs or the PUs. By comparing recent investigations for both interweave and underlay approaches, we can see that the energy harvesting in underlay CRN is more stable in dense areas where a large number of P-Txs are active. Furthermore, the SUs can recognize which channel is the best after energy harvesting, and then use this one for communication without causing harmful interference to the PUs. Although, the energy harvesting in underlay CRN is a promising technique, it still has some disadvantages such as short range communication due to power constraints given by the PU. Also, the spectrum sharing in the underlay CRN may cause mutual interference between the SU and PU as the power allocation policies are not well designed. Moreover, this may lead to leakage of confidential information to the eaversdroppers (EAVs), who want to illegally exploit the communication in CRNs. To overcome the security problems in CRN, works reported in [12]–[14] have focused on solutions at the physical layer in order to reduce the risk of eavesdropping or jamming attacks. In [12], the authors consider a system model where a friendly jammer harvests energy from the RF of the secondary transmitter (S-Tx) and then generates jamming signals to protect against EAV. Asymptotic closed-form expressions of the outage probability and the intercept probability for Nakagami-m fading channels have been obtained to analyze the system performance. In [15], an energy harvesting CRN in which multiple energy harvesting receivers may act as potential EAVs, was studied for small scale fading and path loss. Exact secrecy outage probability was derived. In [14], a wireless energy harvesting CRN has been analyzed, wherein the SU harvests energy from a wireless power source and then uses it to transmit data opportunistically on an idle channel licensed to the PUs. However, the performance of the SUs in this CRN may be degraded very fast due to jamming attacks by malicious users. To overcome these issues, learning algorithms have been proposed to reduce negative effects from unfriendly jammers.

Although many interesting results have been published in RF energy harvesting for CRN, no one addresses the problem of utilizing the interference from multiple PUs to harvest the energy, reduce the affect of EAV, and at the same time enhance the reliability of the communication for CRNs. Therefore, in this paper, we study underlay energy harvesting CRN to not only enhance spectrum efficiency and green energy utilization, but also guarantee a certain security constraint for the SU. In particular, we consider a CRN in which the SU can harvest energy radiated by multiple PUs operating in orthogonal channels and then uses this energy for communication. Here, the SU is overheard by multiple EAVs. To protect the confidential information of the SU from the EAVs and not to violate the interference constraint of the PU, the S-Tx must have a reasonable channel selection strategy and power allocation. Given these settings, the analysis for the considered CRN is twofold, namely as packet error probability and packet delay with retransmissions. Our main contributions are summerized as follows:

- An energy harvesting and communication protocol over multiple PU channels is proposed. Accordingly, an optimal energy harvesting time for the SU is derived.
- A power allocation policy and a channel selection strategy for the SU, which satisfy the interference constraint of the PU and its own security constraints for multiple EAVs is developed.
- To evaluate the system performance of the SU, closed-form expressions for the packet error probability and packet delay including retransmission for the SU are derived.

The rest of this paper is structured as follows. In Section II, the system model, power constraints, and energy harvesting and communication protocol for the energy harvesting CRN are introduced. In Section III, the power allocation and channel selection strategy are analyzed. Further, an optimal energy harvesting time, and algorithm for power allocation and channel selection are proposed. In Section IV, closed-form expressions of packet error probability and packet delay with retransmissions are obtained. In Section V, the numerical examples and discussions are provided. Finally, conclusions are given in Section VI.

II. System Model

In this section, the system model, and energy harvesting and communication protocol are presented.

A. System model and channel assumptions

Let us consider a spectrum underlay CRN as shown in Fig. 1 in which N PUs are operating on orthogonal frequency bands, i.e., they do not cause interference to each other. The S-Tx harvests energy from N P-Txs and then uses this harvested energy to send packets to the secondary access point (SAP). Further, there exist K EAVs wishing to overhear the packet transmitted from the S-Tx to the SAP. Here, the SAP is equipped with M antennas while the others (P-Tx, primary receiver (P-Rx), EAV, and S-Tx) is assumed to have a single antenna. Channel gains of the P-Tx$_n\rightarrow$P-Rx$_n$ and S-Tx$\rightarrow$SAP communication links are denoted h_n, and g_m, $n = 1,\dots,N$, $m = 1,\dots,M$. Here, the channel gain g_m is to represent the link from the S-Tx to the m-antenna branches of the SAP. The channel gains of the P-Tx$_n\rightarrow$EAV$_k$, S-Tx$\rightarrow$P-Rx$_n$, P-Tx$_n\rightarrow$SAP interference links are denoted by β_{nk}, α_n, and ρ_{nm}, respectively. The channel gains of the S-Tx$\rightarrow$EAVs illegitimate links and the P-Tx$_n\rightarrow$S-Tx energy harvesting links are expressed, respectively, by δ_k and f_n, $k \in \{1,\dots,K\}$. We assume that all channels are modeled as Rayleigh block flat fading, and the channel gains are random variables (RVs) distributed following exponential distribution. Accordingly, the probability density function (PDF) and

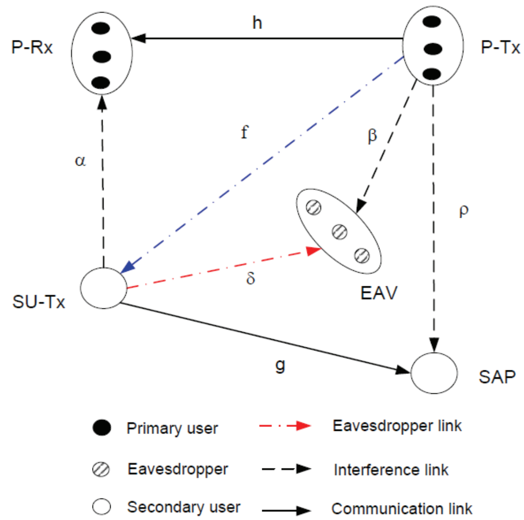

Fig. 1. A system model of underlay CRN. The S-Tx scavenges the energy from multiple P-Tx and spends this harvested energy to deliver packet to the SAP. The S-Tx is overheard by multiple EAVs.

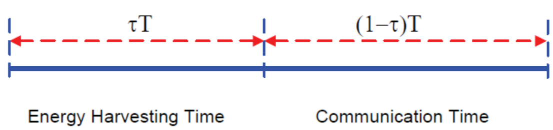

Fig. 2. A time frame T is used for energy harvesting and communication. The time τT is used to harvest energy from the multiple P-Txs, while the remaining time $(1-\tau)T$ is to deliver the packet to the SAP.

cumulative distribution function (CDF) are expressed, respectively, as

$$f_X(x) = \frac{1}{\Omega_X} \exp\left(-\frac{x}{\Omega_X}\right), \tag{1}$$

$$F_X(x) = 1 - \exp\left(-\frac{x}{\Omega_X}\right), \tag{2}$$

where RV $X \in \{g_m, h_n, f_n, \alpha_n, \delta_k, \beta_{nk}, \rho_{nm}\}$, refers to the channel gain, and $\Omega_X = \mathbf{E}[X]$ is the channel mean gain, i.e., $\Omega_g = \mathbf{E}[g_m]$, $\Omega_{h_n} = \mathbf{E}[h_n]$, $\Omega_{\alpha_n} = \mathbf{E}[\alpha_n]$, $\Omega_\delta = \mathbf{E}[\delta_k]$, $\Omega_{\beta_n} = \mathbf{E}[\beta_{nk}]$, $\Omega_{\rho_n} = \mathbf{E}[\rho_{nm}]$.

B. Communication protocol

The basic idea of the RF energy harvesting in the considered CRN is that the S-Tx can convert the P-Tx emitted power, which is considered as harmful interference to the SU, into useful energy for the SU communication. The total time used for energy harvesting and communication is showed in Fig. 2. Accordingly, the communication protocol is implemented in two steps as follows:

- Step 1: The S-Tx harvests the energy of N P-Tx over N wireless links f_n, $n \in \{1, 2, \ldots, N\}$. The average harvested energy at the S-Tx can be expressed as follows:

$$E_s = \mathbf{E}\left[\sum_{n=1}^{N} \theta\tau T P_p f_n\right] = \theta\tau T P_p \, \mathbf{E}\left[\sum_{n=1}^{N} f_n\right], \tag{3}$$

  where $\mathbf{E}[\cdot]$, T, and τ are expectation, the total time frame, and a fraction of time frame used to harvest the wireless energy, respectively, $0 < \tau < 1$. Symbols P_p and θ represent the transmit power of the P-Tx and the energy harvesting efficiency coefficient of the S-Tx, $0 \le \theta \le 1$.
- Step 2: After the energy harvesting process, the S-Tx also completes the channel state information (CSI) estimation, and it may know which is the best frequency band for the SU communication. Here, the best channel is the one that allows the S-Tx to use maximal transmit power to improve the performance. It is noted that the transmit power of the S-Tx in the remaining timeslot $(1-\tau)T$ and at the specific channel n-th is constrained by the harvested energy E_s, i.e, $P_{S-Tx}^{(n)}(1-\tau)T \le E_s$. Accordingly, we have

$$P_{S-Tx}^{(n)} \le P_{avg} = \frac{E_s}{(1-\tau)T} = \frac{\tau\theta P_p}{1-\tau} \sum_{n=1}^{N} \Omega_{f_n}, \tag{4}$$

  where P_{avg} is called as average power threshold given by the S-Tx. On this basis, power allocation under various constraints and channel selection process for the SU can be derived.

III. Power Allocation and Channel Selection of the SU

In order to deliver packets to the SAP, the S-Tx firstly calculates the power allocation strategy in each channel to guarantee the quality of service (QoS) constraint of the PU and not reveal its confidential information to the EAVs.

1) Power constraint of the S-Tx under PU's constraint: Since the SU utilizes one of the N channels licensed to the PUs, its power control policy should be designed to not cause the harmful interference to the PU while obtaining the maximal power level to improve the performance. These can be interpreted into the outage probability constraint given by the PU η_p, and the average power threshold given by the S-Tx as follows:

$$\Pr\left\{C_p^{(n)} \le R_p\right\} \le \eta_p, \tag{5}$$

$$P_{S-Tx}^{(n)} \le P_{avg}, \tag{6}$$

where R_p, η_p, and P_{avg} are the target rate, outage constraint of the PU, and average power constraint of the

S-Tx, respectively. Symbol $C_p^{(n)}$ is the channel capacity of the PU at the n-th frequency band, defined as

$$C_p^{(n)} = B\log_2\left(1+\gamma_p^{(n)}\right), \tag{7}$$

where B is bandwidth and $\gamma_p^{(n)}$ is signal-to-interference-plus-noise ratio (SINR) of the PU given as

$$\gamma_p^{(n)} = \frac{P_p h_n}{P_{S-Tx}^{(n)}\alpha_n + N_0}, \tag{8}$$

in which the symbol N_0 is noise power.

By substituting (8) and (7) into (5), we can rewrite (5) as follows

$$\Pr\left\{\frac{P_p h_n}{P_{S-Tx}^{(n)}\alpha_n + N_0} \le \gamma_{th}^p\right\} \le \eta_p, \tag{9}$$

where $\gamma_{th}^p = 2^{\frac{R_p}{B}} - 1$. Further, using [16, Property 1], the expression (9) can be calculated as

$$1 - \frac{P_p\Omega_{h_n}}{P_{S-Tx}^{(n)}\Omega_{\alpha_n}\gamma_{th}^p + P_p\Omega_{h_n}}\exp\left(-\frac{\gamma_{th}^p N_0}{P_p\Omega_{h_n}}\right) \le \eta_p \tag{10}$$

By setting $A_n = \frac{\gamma_{th}^p\Omega_{\alpha_n}}{P_p\Omega_{h_n}}$, $B_n = \frac{\gamma_{th}^p N_0}{P_p\Omega_{h_n}}$, we can rewrite (10) as

$$P_{S-Tx}^{(n)} \le \frac{1}{A_n}\left[\frac{\exp(-B_n)}{1-\eta_p} - 1\right]. \tag{11}$$

Combining (11) with (6), the transmit power of the S-Tx should satisfy both PU's outage constraint and its own harvested energy as

$$P_{S-Tx}^{(n)} \le \min\left\{P_{PU}^{(n)}, P_{avg}\right\}, \tag{12}$$

where $P_{PU}^{(n)}$ is formulated as

$$P_{PU}^{(n)} = \frac{1}{A_n}\left[\frac{\exp(-B_n)}{1-\eta_p} - 1\right]. \tag{13}$$

2) Power constraint of the S-Tx under the overhearing of multiple EAVs: The confident communication of the SU is threaten by K EAVs. Therefore, the S-Tx should regulate its power to not reveal the information to the EAVs. This can be interpreted into the outage security and transmit power constraints of the S-Tx as follows

$$\Pr\left\{\max_{k\in\{1,\dots,K\}}\left\{C_e^{(n,k)}\right\} \ge R_e\right\} \le \xi, \tag{14}$$

$$P_{S-Tx}^{(n)} \le P_{avg}, \tag{15}$$

where R_e and ξ are the secrecy target rate and the secrecy outage constraint, respectively. Symbol $C_e^{(n,k)}$ denotes the channel capacity of the EAV$_k$ over the S-Tx$\rightarrow$EAV$_k$ link when the S-Tx selects the frequency band n to transmit, defined as

$$C_e^{(n,k)} = B\log_2\left(1+\gamma_e^{(n,k)}\right), \tag{16}$$

in which $\gamma_e^{(n,k)}$ is the SINR of the EAV$_k$ at the n-th frequency band, and it can be approximated as

$$\gamma_e^{(n,k)} = \frac{P_{S-Tx}^{(n)}\delta_k}{P_p\beta_{nk} + N_e} \approx \frac{P_{S-Tx}^{(n)}\delta_k}{P_p\beta_{nk}}, \tag{17}$$

where N_e is noise power at the EAVs. The approximation (17) is understood that the interference from the P-Tx to the EAV is much larger than the background noise power, i.e. $P_p\beta_{nk} >> N_e$, and the EAVs only are affected by the interference from the P-Tx.

Substituting (16) into (14), we have

$$\Pr\left\{\max_{k\in\{1,2,\dots,K\}}\{B\log_2(1+\gamma_e^{(n,k)})\} \ge R_e\right\} \le \xi. \tag{18}$$

Since all channels are independent random variables, the expression (18) can be formulated as

$$1 - \prod_{k=1}^{K}\underbrace{\Pr\left\{\frac{\delta_k}{\beta_{nk}} \le \frac{\gamma_{th}^e P_p}{P_{S-Tx}^{(n)}}\right\}}_{I} \le \xi, \tag{19}$$

where $\gamma_{th}^e = 2^{\frac{R_e}{B}} - 1$. Further, the probability in (19) can be derived as

$$I = \int_0^\infty \Pr\left\{\delta_k \le \frac{x\gamma_{th}^e P_p}{P_{S-Tx}^{(n)}}\right\} f_{\beta_{nk}}(x)dx, \tag{20}$$

where $f_{\beta_{nk}}(x) = \frac{1}{\Omega_{\beta_n}}\exp\left(-\frac{x}{\Omega_{\beta_n}}\right)$. Accordingly, the integral I can be calculated as

$$\begin{aligned} I &= 1 - \int_0^\infty \frac{1}{\Omega_{\beta_n}}\exp\left[-\left(\frac{\gamma_{th}^e P_p}{P_{S-Tx}^{(n)}\Omega_\delta} + \frac{1}{\Omega_{\beta_n}}\right)x\right]dx \\ &= 1 - \frac{1}{\frac{\gamma_{th}^e P_p\Omega_{\beta_n}}{P_{S-Tx}^{(n)}\Omega_\delta} + 1}. \end{aligned} \tag{21}$$

Substituting (21) into (19) and after some mathematical manipulations, we obtain the power constraint for the S-Tx to against multiple eavesdroppers as follows

$$P_{S-Tx}^{(n)} \le \frac{\gamma_{th}^e P_p\Omega_{\beta_n}(1-\sqrt[K]{1-\xi})}{\Omega_\delta\sqrt[K]{1-\xi}}. \tag{22}$$

Combining (22) with the energy harvesting constraint (15) yields

$$P_{S-Tx}^{(n)} \le \min\left\{P_{Eav}^{(n)}, P_{avg}\right\}, \tag{23}$$

where $P_{Eav}^{(n)}$ is expressed as

$$P_{Eav}^{(n)} = \frac{\gamma_{th}^e P_p\Omega_{\beta_n}(1-\sqrt[K]{1-\xi})}{\Omega_\delta\sqrt[K]{1-\xi}} \tag{24}$$

As a consequence, the transmit power of the S-Tx in the n-th channel is obtained by combining (12) with (23) as

$$P_{S-Tx}^{(n)} = \min\left\{\min\{P_{PU}^{(n)}, P_{Eav}^{(n)}\}, P_{avg}\right\}. \tag{25}$$

From (25), we consider two case as follows:

- *Case 1:* $P_{avg} > \min\{P_{PU}^{(n)}, P_{Eav}^{(n)}\}$, the transmit power of the S-Tx depends on the joined constraints of the PU and EAV as

$$P_{S-Tx}^{(n)} = \min\{P_{PU}^{(n)}, P_{Eav}^{(n)}\}, \tag{26}$$

where $P_{PU}^{(n)}$ and $P_{Eav}^{(n)}$ are defined in (13) and (24), respectively. Note that if the energy harvesting time τ in this case is increase further, the transmit power of the S-Tx can not increase further due to the joint constraint of the PU and EAVs.

- *Case 2:* $P_{avg} \le \min\{P_{PU}^{(n)}, P_{Eav}^{(n)}\}$, the maximal transmit power of the S-Tx depends on the harvested energy from the PUs, i.e., $P_{S-Tx}^{(n)} = P_{avg}$. Moreover, the S-Tx expects to have a high value of P_{avg} to obtain the high performance, this leads to a fact that the maximal P_{avg} is equal to $\min\{P_{PU}^{(n)}, P_{Eav}^{(n)}\}$, i.e., $P_{avg} = \min\{P_{PU}^{(n)}, P_{Eav}^{(n)}\}$. After some mathematical manipulations, we obtain the optimal energy harvesting time τ for maximizing the value of P_{avg} as

$$\tau^* = \frac{\min\{P_{PU}^{(n)}, P_{Eav}^{(n)}\}}{\theta P_p \sum_{n=1}^{N} \Omega_{f_n} + \min\{P_{PU}^{(n)}, P_{Eav}^{(n)}\}}. \tag{27}$$

Moreover, the S-Tx wants to select the best channel to maximize its transmit power to improve its performance, and this is given as

$$n^* = \arg \max_{n \in \{1,2,\ldots,N\}} \left\{ P_{S-Tx}^{(n)} \right\}, \tag{28}$$

where n^* is the selected channel such that the transmit power of the S-Tx is optimal, i.e.,

$$P_{S-Tx}^{(n^*)} = \max_{n \in \{1,2,\ldots,N\}} \left\{ \min \left\{ \min\{P_{PU}^{(n)}, P_{Eav}^{(n)}\}, P_{avg} \right\} \right\}.$$

Finally, an algorithm for the power allocation and channel selection is shown in Algorithm 1.

Algorithm 1 Power allocation and channel selection

procedure PASA
    $P_{S-Tx}^{(n^*)} := 0$;
    for $\{n = 1; n \le N; n++\}$ **do**
        $P_{PU}^{(n)} = \frac{1}{A_n}\left[\frac{\exp(-B_n)}{1-\eta_p} - 1\right]$;
        $P_{Eav}^{(n)} = \frac{\gamma_{th}^{e} P_p \Omega_{\beta_n}(1 - \sqrt[K]{1-\xi})}{\Omega_\delta \sqrt[K]{1-\xi}}$;
        $\tau = \frac{\min\{P_{PU}^{(n)}, P_{Eav}^{(n)}\}}{\theta P_p \sum_{n=1}^{N} \Omega_{f_n} + \min\{P_{PU}^{(n)}, P_{Eav}^{(n)}\}}$;
        $P_{avg} = \frac{\tau \theta P_p}{1-\tau} \sum_{n=1}^{N} \Omega_{f_n}$;
        $P_{S-Tx}^{(n)} = \min\left\{\min\{P_{PU}^{(n)}, P_{Eav}^{(n)}\}, P_{avg}\right\}$;
        if $P_{S-Tx}^{(n)} \ge P_{S-Tx}^{(n^*)}$ **then**
            $n^* = n$;
            $P_{S-Tx}^{(n^*)} = P_{S-Tx}^{(n)}$
    return n^* and $P_{S-Tx}^{(n^*)}$;

IV. Performance Analysis

When the S-Tx sends packets, they may be in error due to channel impairment and other factors. Thus, the S-Tx needs to recharge and retransmit. In order to measure this process, we will consider two performance metrics, called packet error probability (PEP) and average packet delay (APD), as follows:

1) Packet Error Probability: The PEP is defined as the probability that the SINR of the SU drops below a predefined threshold, i.e.,

$$\mathcal{O} = \Pr\{\gamma_s \le \gamma_{th}\}, \tag{29}$$

where γ_{th} is the SINR threshold of the SU and γ_s is defined as

$$\gamma_s = \max_{m \in \{1,2,\ldots,M\}} \left\{ \frac{P_{S-Tx}^{(n^*)} g_m}{P_p \rho_{n^* m} + N_0} \right\}. \tag{30}$$

Accordingly, the PEP can be calculated by using order statistics and the help of [16, Property 1] as follows:

$$\begin{aligned} \mathcal{O} &= \Pr\left\{ \max_{m \in \{1,2,\ldots,M\}} \left\{ \frac{P_{S-Tx}^{(n^*)} g_m}{P_p \rho_{n^* m} + N_0} \right\} < \gamma_{th} \right\} \\ &= \prod_{m=1}^{M} \Pr\left\{ \frac{P_{S-Tx}^{(n^*)} g_m}{P_p \rho_{n^* m} + N_0} < \gamma_{th} \right\} \\ &= \left(1 - \frac{\exp\left(-\frac{\gamma_{th} N_0}{P_{S-Tx}^{(n^*)} \Omega_g}\right)}{\frac{\gamma_{th} P_p \Omega_{\rho_{n^*}}}{P_{S-Tx}^{(n^*)} \Omega_g} + 1} \right)^M. \end{aligned} \tag{31}$$

2) Packet Delay With Retransmissions: when a packet is transmitted unsuccessfully, the S-Tx needs to recharge the energy and then retransmit. The probability that a packet is transmitted successfully after ℓ transmissions is expressed as follows:

$$\Pr\{L = \ell\} = \mathcal{O}^{\ell-1}(1 - \mathcal{O}), \tag{32}$$

where L is the number of transmissions. Accordingly, the average number of transmissions per packet can be calculated as

$$\mathbf{E}[L] = \sum_{\ell=1}^{\infty} \ell \mathcal{O}^{\ell-1}(1 - \mathcal{O}) = \frac{1}{1 - \mathcal{O}}. \tag{33}$$

Finally, the average delay to transmit a packet can be calculated as follows:

$$D = T\,\mathbf{E}[L] = \frac{T}{1 - \mathcal{O}}, \tag{34}$$

where T is total time frame and $\mathcal{O}$ is PEP defined in (29).

V. NUMERICAL RESULTS

In this section, we present numerical examples for the considered system. In particular, we investigate the impact of the P-Tx transmit signal-to-noise ratio (SNR), energy harvesting time, and the channel mean gains on the PEP and APD. Unless otherwise stated, the following system parameters are used for both analysis and simulation: System bandwidth: $B = 2$ MHz; Outage constraint of PU: $\eta_p = 0.01$; Security constraint: $\xi = 0.01$; Energy harvesting coefficient efficiency: $\theta = 0.5$; Target rate of SU, PU, and EAVs are $R_s = 64$ Kbps, $R_s = 64$ Kbps, and $R_e = 3$ Mbps, respectively.

Fig. 3 illustrates the impact of channel mean gains of the P-Tx→EAVs links (Ω_{β_n}) on the S-Tx transmit SNR. We can see that the index C, which is equivalent to the channel 2 and $\Omega_{\beta_2} = 500$, provides the highest S-Tx transmit SNR. On the other hand, the index D, which is equivalent to the channel 3 and $\Omega_{\beta_3} = 100$, provides the lowest S-Tx transmit SNR. This is due to the fact that a higher channel mean gain of the P-Tx→EAVs leads to a stronger interference to the EAVs, i.e., the EAVs experience difficulties to decode the transmitted packet from the S-Tx. As a result, the S-Tx can increase its transmit power to enhance its performance without leaking confidential information to the EAVs. In other words, channel 2 will be selected for the SU communication. This phenomenon can be observed from Fig. 3, i.e., increasing the channel mean gains of the P-Tx→ EAVs links (Ω_{β_n}) leads to scaling up of the P-Tx transmit SNR, or the interference from the P-Tx to the EAVs brings benefit for the S-Tx transmit SNR.

Fig. 5 shows the impact of the fraction of the energy harvesting time τ and channel mean gains of P-Tx→S-Tx energy harvesting links $\{\Omega_{f_n}\}_{n=1}^{5} = 1, 3, 5$ on the S-Tx transmit SNR. It can be seen that when the channel mean gain of the P-Tx→S-Tx harvesting link is the

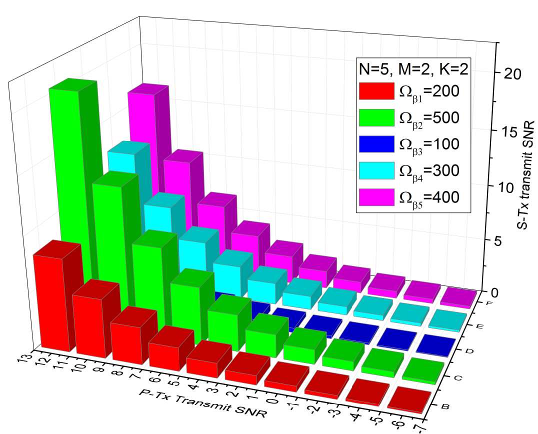

Fig. 3. Impact of channel mean gains of the P-Tx→EAVs links (Ω_{β_n}) on the S-Tx transmit SNR.

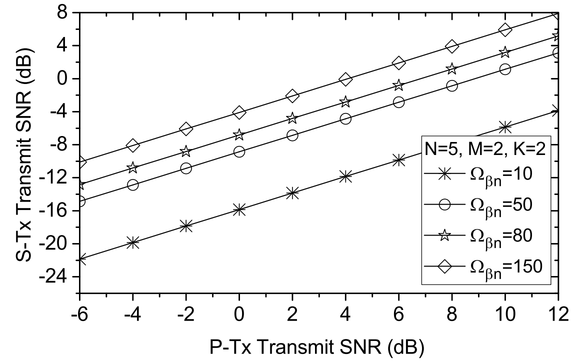

Fig. 4. The S-Tx transmit SNR versus the P-Tx transmit SNR with increasing channel mean gains of the S-Tx→EAV link $\{\Omega_{\beta_n}\}_{n=1}^{5} = 10, 50, 80, 150$.

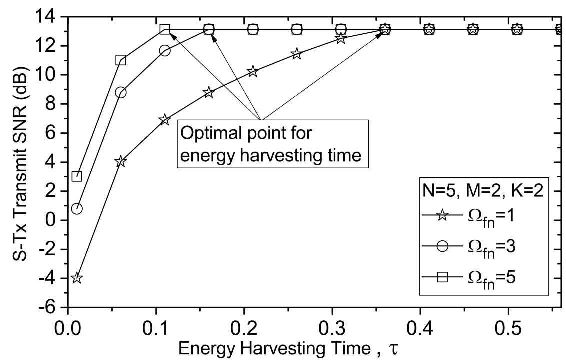

Fig. 5. The SU transmit SNR versus the energy harvesting time τ and the channel mean gains of P-Tx→S-Tx energy harvesting links $\{\Omega_{f_n}\}_{n=1}^{5} = 1, 3, 5$, and $\gamma_{P-Tx} = 12$ dB.

highest, i.e., $\{\Omega_{f_n}\}_{n=1}^{5} = 5$, the S-Tx transmit SNR is increased very fast and saturated at $\tau = 0.1$. Also, all S-Tx transmit SNR is saturated at the same value 13 dB as $\tau > 0.4$, i.e., the energy harvesting time does not affect the S-Tx transmit SNR. This can be explained as follows: the higher channel mean gain of the P-Tx→S-Tx link leads to a higher energy harvested from the P-Txs, thus the time consumed τ to harvest the energy is shorter. However, increasing the energy harvesting time further, i.e. $\tau > 0.4$, the S-Tx cannot harvest more energy due to the fixed transmit SNR of the P-Txs $\gamma_{P-Tx} = 12$ dB, i.e., the S-Tx transmit SNR is saturated.

Fig. 6 shows the impact of the P-Tx→EAV interference links on the PEP by consider the following cases:

- Case 1: Channel mean gains of the P-Tx→EAVs interference links are identical: $\{\Omega_{\beta_n}\}_{n=1}^{5} = 10$;
- Case 2: Channel mean gain of from the P-Tx$_5$→EAVs interference links is the highest: $\Omega_{\beta_5} = 50$, the other is identical: $\{\Omega_{\beta_n}\}_{n=1}^{4} = 10$;
- Case 3: Channel mean gain of from the P-Tx$_1$→EAVs interference links is the highest: $\Omega_{\beta_1} = 100$, the other is identical: $\{\Omega_{\beta_n}\}_{n=2}^{4} = 10$;
- Case 4: Channel mean gains of the P-Tx→EAVs

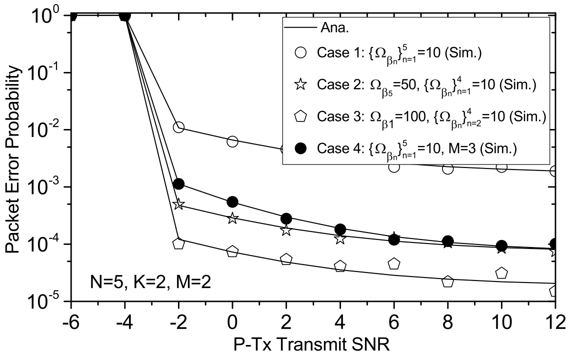

Fig. 6. Channel mean gain of P-Tx→P-Rx links: $\{\Omega_{h_n}\}_{n=1}^5 = 2$; Channel mean gain of S-Tx→P-Rx links: $\{\Omega_{\alpha_n}\}_{n=1}^5 = 2$; Channel mean gain of P-Tx→S-Tx links: $\{\Omega_{f_n}\}_{n=1}^5 = 5$; Channel mean gain of S-Tx→EAVs links: $\{\Omega_{\delta_k}\}_{k=1}^2 = 1$; Channel mean gain of P-Tx→SAP links $\{\Omega_{\rho_{nm}}\} = 1$ for all n and m; Channel mean gain of S-Tx→SAP links $\Omega_g = 8$;.

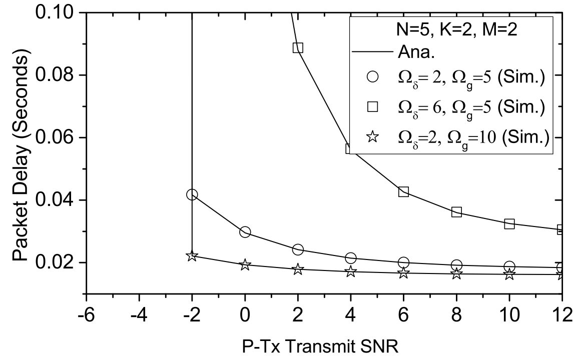

Fig. 7. Packet delay versus P-Tx transmit SNR. Channel mean gain of P-Tx→P-Rx links: $\{\Omega_{h_n}\}_{n=1}^5 = 2$; Channel mean gain of S-Tx→P-Rx links: $\{\Omega_{\alpha_n}\}_{n=1}^5 = 2$; Channel mean gain of P-Tx→S-Tx links: $\{\Omega_{f_n}\}_{n=1}^5 = 5$; Channel mean gain of P-Tx→EAVs links: $\{\Omega_{\beta_n}\}_{n=1}^5 = 2$; Channel mean gain of P-Tx→SAP links $\{\Omega_{\rho_{nm}}\} = 1$ for all n and m; Channel mean gain of S-Tx→SAP links $\Omega_g = 5$;.

interference links are identical as in Case 1. But the number of antennas of the SAP is greater than the one of Case 1, i.e., $M = 3$.

It can be seen from Case 1 to Case 3 that if one of the channels has the strongest P-Tx→EAV interference links, it is selected for communication and the PEP is degraded significantly. More specifically, the PEP in Case 3 is better than the one in Case 1 and Case 2. This can be explained by the fact that the strong interference from the P-Tx to the EAVs degrades the quality of packets decoded at the EAVs. Accordingly, the S-Tx can increase its transmit SNR to enhance its performance without leaking confidential information to the EAVs. Further, we see that the PEP in Case 4 is better than the one in Case 1. Because the number of antennas of the SAP in Case 4 is higher than Case 1, and hence its received signal is better than Case 1. As a result, the PEP in Case 4 is reduced.

Fig. 7 shows the impact of the S-Tx→EAVs and S-Tx→SAP links on the packet delay. We can see that at the low P-Tx transmit SNR regime, e.g. $\gamma_{P-Tx} < -2$ dB, the packet delay goes to infinity. However, as the P-Tx transmit SNR increases further, the packet delay of the SU is reduced significantly. This is because the S-Tx only harvests small amounts of energy at the low P-Tx transmit SNR, thus the power required to deliver the packet is very low, which increases the packet error rate. Hence, the S-Tx requires several retransmissions to deliver the packet, i.e., the packet delay increases. Further, as the channel mean gain of the S-Tx→EAVs links increase from $\Omega_\delta = 2$ to $\Omega_\delta = 6$, the packet delay also increases. This is due to the fact that the EAVs can decode the packet from the S-Tx more easily as the channel mean gain of the S-Tx→EAVs links increase. To guarantee secure communication, the S-Tx must reduce its transmit SNR to satisfy the security constraint. Accordingly, the packet error rate is increased, i.e., the S-Tx requires more retransmissions. Thus, the packet delay increases. It also can be seen that as the channel mean gain of the S-Tx→SAP link increases from $\Omega_g = 5$ to $\Omega_g = 10$, the packet delay is improved significantly. It is easy to understand that as all constraints are satisfied, a strong channel gain between the source and the destination will guarantee a low packet error rate, i.e, the S-Tx does not have to retransmit the packet.

VI. CONCLUSIONS

In this paper, we have proposed an energy harvesting and communication protocol for CRNs, in which the S-Tx is subject to the harvested energy constraint, security constraints due to multiple EAVs, and outage probability constraint of the PU. The optimal energy harvesting time, a power allocation policy and a channel selection strategy have been derived. Moreover, performance analysis in terms of packet error probability and average packet delay including retransmissions for the secondary network has been obtained. Further, our numerical results show that the proposed power allocation policy and channel selection strategy can provide reliable and secure communication for the SU without violating the security constraints and interference constraints due to multiple PU. Finally, the analytical results are verified by simulations.

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