Opportunistic Ambient Backscatter Communication in RF-Powered Cognitive Radio Networks

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***Abstract*—We propose a novel opportunistic ambient backscatter communication (ABC) framework for radio frequency (RF)-powered cognitive radio (CR) networks. The proposed framework considers opportunistic spectrum sensing integrated with ABC and harvest-then-transmit (HTT) operation strategies. Novel analytic expressions are derived for the average throughput, average energy consumption and energy efficiency in the considered set up. In addition, we formulate an optimization problem to maximize the energy efficiency of the CR system operating in mixed ABC− and HTT−modes, subject to primary interference and energy harvesting constraints. Next, we determine the optimal set of parameters which in turn comprise the optimal detection threshold, and the optimal degree of tradeoff between the CR system operating in the ABC− and HTT−modes. We present extensive numerical results to corroborate our analysis and to demonstrate the performance gain of the proposed model in terms of energy efficiency.**

I. Introduction

The integration of RF energy harvesting techniques [1] with cognitive radio networks (CRNs) [2] has introduced a cutting-edge technology which has lead to the development of a new communication paradigm, known as *RF-powered CRNs* [3], [4], [5]. In an RF-powered CRN, a CR transmitter harvests RF energy when a primary user (PU) is declared to be present and utilizes it for data transmission when the spectrum is declared vacant. This protocol is referred to as *harvest-then-transmit* (HTT) protocol [6], [7]. However, a major challenge associated with this method is the reduction of the throughput of the CRN when the harvested energy is low and/or when the data transmission time is shorter. To overcome this shortcoming, the concept of ambient backscatter communication (ABC), a technology that requires low power and low cost [8], [9], has been employed in RF-powered CRNs [7]. In ABC, ambient signals such as TV or WiFi signals are backscattered by a transmitter to convey information to a receiver. Likewise, a CR transmitter can send data to CR receiver by backscattering a PU signal when it is present.

Clearly, the performance of both HTT-based CRNs and ABC-based CRNs depend on the availability of PU signals, which represents a major challenge for CR networks particularly during the long idle period [10], [11]. This requires a paradigm shift towards the development of key enabling techniques for next generation CR networks, such as the hybrid ABC-HTT schemes which were recently proposed in [7]. However, a common and major drawback in the proposed models is the assumption of perfect knowledge of PU activities, which is largely unrealistic in practice.

In light of the above, we propose a novel opportunistic hybrid ABC-HTT model for CRNs, coined as *ABC-HTT-based CRNs* which exploits the potential of both ABC and RF-powered CRNs. In particular, we analyze the energy efficiency (EE) performance of an ABC-HTT-based CRN in the presence of sensing errors and without assuming knowledge of the statistics of PU activity. For simplicity, we consider energy detection-based spectrum sensing, which has widely known advantages. Then, we derive analytic expressions for the average achievable throughput and average energy consumption followed by a detailed formulation of an optimization problem that maximizes the EE subjected to several constraints, including the interference constraint on PU. Subsequently, we derive the expressions for the optimal detection threshold and optimal energy harvesting time, and then quantify the tradeoff between the ABC and HTT modes, all in terms of EE. The main contributions of this work are summarized below:

- We propose a novel opportunistic ABC framework for RF-powered CRNs in the presence of sensing errors, which operates in combination with the existing HTT mode, called as a *ABC-HTT-based CRN*.
- We derive novel analytic expressions for the average achievable throughput, the average energy consumption and the energy efficiency of the proposed network.
- We formulate an optimization problem that maximizes the EE of the considered network, and evaluate the optimal threshold and energy harvesting time, subject to PU interference and energy harvesting constraints.

- We validate our analysis through detailed numerical results, and evaluate the EE performance of the CRN in the presence of sensing errors. Furthermore, we quantify the tradeoff between ABC-and HTT-modes in terms of EE. It is shown that the proposed ABC-HTT-based CRN exhibits an improved energy efficiency performance.

To the best of our knowledge, no energy efficiency analyses in the presence of sensing errors for ABC-HTT-based CR networks have been reported in the open literature.

II. Network Model

We consider an ABC-HTT-based CRN, as shown in Fig. 1, which consists of a secondary user transceiver pair, denoted by (ST, SR), and a primary transceiver pair, denoted by (PT, PR). We model the CR network in the opportunistic spectrum access (OSA) paradigm, in which the PU channels are accessed opportunistically using SS to detect spectrum holes. The ST is equipped with an energy-based SS unit, an RF energy harvesting unit and an ABC unit. The time diagram for the proposed model is shown in Fig. 1; based on this, when the PT is declared present, the ST can harvest energy and store it in a battery, or perform ABC for data transmission, as shown in Fig. 1(a). In this case, the network is in the *ambient backscatter communication* (ABC) mode, where τ denotes the normalized data transmission period, and $(1-\tau)$ denotes the normalized sensing duration of the secondary user transceiver pair. Furthermore, we let $\alpha\tau$ represent the time fraction utilized for energy harvesting and $(1-\alpha)\tau$ represent the time fraction for ABC, when the PT-PR channel is declared occupied. The harvested energy during the time $\alpha\tau$ is stored in the ST battery, in order to be used for data transmission over the ST-SR link, when the PT-PR channel is idle. On the contrary, when the PT is declared absent, the ST uses the harvested energy to transmit data to SR for a duration of τ. In this case, the network is considered to be in the *harvest-then-transmit* (HTT) mode, as shown in Fig. 1(b).

It is recalled that in the present set up, we consider energy detection-based SS, owing to its numerous advantages such as simple realization and moderate computational complexity [12]. Based on this, the probabilities of false-alarm and signal detection at the ST are respectively given by [13]

$$P_f = Q\left[\left(\frac{\varepsilon}{\sigma^2}-1\right)\sqrt{(1-\tau)N_s}\right] \tag{1}$$

and

$$P_d = Q\left[\left(\frac{\varepsilon}{\sigma^2}-\gamma-1\right)\sqrt{\frac{(1-\tau)N_s}{2\gamma+1}}\right], \tag{2}$$

where $N_s = f_s T_t$ denotes the number of observations, f_s is the sampling frequency, T_t is the duration of the entire frame, σ^2 is the noise variance, ε is the detection threshold, and γ denotes the received SNR at ST. Furthermore, $Q(\cdot)$ denotes the complementary CDF of a standard Gaussian distribution.

It was recently shown that switching between these two modes improves the overall throughput of the secondary system [7]. A similar idea is adopted in the present contribution with the difference that our analysis concerns the study of a CR network operating in ABC-HTT framework, using the OSA paradigm in the presence of the sensing errors in terms of P_f and P_d, as opposed to the analysis in [7] which considers CR operation in the overlay mode. In addition, we quantify the performance of the proposed model in terms of energy efficiency of the CR network in the presence of sensing errors, unlike [7] that analyzes the throughput performance in the simplistic case of ideal sensing, i.e. no sensing errors.

III. Energy Efficiency and Problem Formulation

It is recalled that the energy efficiency of the CR network is defined as the ratio of its average achievable throughput to its average energy consumption [14], [15]. In what follows, we calculate the energy efficiency of the proposed model and then formulate an optimization problem that enables the calculation of the optimal values of ε, α and τ that maximize the energy efficiency, under PU interference and energy harvesting constraints. It is noted that due to the presence of the sensing mechanism, the average achievable throughput depends on the sensing accuracy and the communication link between PT and ST. This can be categorized into the following four scenarios. Here, $P(\mathcal{H}_0)$ and $P(\mathcal{H}_1)$ denote the prior probabilities of the PT being inactive and active, respectively.

S1: In this scenario, the ST correctly declares the presence of the PT with probability $P(\mathcal{H}_1)P_d$. Hence, the throughput is achieved due to ST using only the ABC mode, which is

$$R_{b,S_1} = (1-\alpha)\tau B_b, \tag{3}$$

where B_b is the achievable backscatter rate in the ABC mode.

S2: In this scenario, the ST incorrectly declares the PT to be active with probability $P(\mathcal{H}_0)P_f$. This results in a lack of throughput, since the CR network achieves no throughput in the ABC mode. Also, ST misses a transmission opportunity.

S3: In this scenario, the ST incorrectly declares the PT to be absent, with probability $P(\mathcal{H}_1)(1-P_d)$; as a consequence, the ST misses an opportunity to use the ABC mode. Moreover, the ST transmits to SR in the HTT mode and creates interference to the PT. In the presence of the interference from PT, the CR network achieves a partial throughput of

$$R_{h,S_3} = \tau\kappa W \log_2\left(1+\frac{P_{\text{tr}}}{Z_I P_{T,PU}+P_0}\right), \tag{4}$$

with a partial throughput factor $\kappa \in (0,1)$, which quantifies the partial throughput achievable in this scenario, where W is the bandwidth of the primary link, $P_0 = N_0/g_c$ is the ratio between the noise power N_0 and g_c, the channel gain coefficient between ST and SR, P_{tr} denotes the transmit power of the ST in the data transmission period τ, Z_I denotes the ratio of the channel gain between the PT and the ST to g_c, and $P_{T,\text{PU}}$ denotes transmission power of the PU. Next, P_{tr} can be expressed as $P_{\text{tr}} = (E_{\text{h}} - E_{\text{s}} - E_{\text{c}})/\tau$, where $E_{\text{s}} = P_s(1-\tau)$ is the energy consumed during sensing, $E_{\text{c}} = \tau P_c$ is the energy consumption of the circuitry in the transmission time τ, $E_{\text{h}} = \alpha\tau P_R$ is the total harvested energy, and P_R is the harvested RF power obtained from the

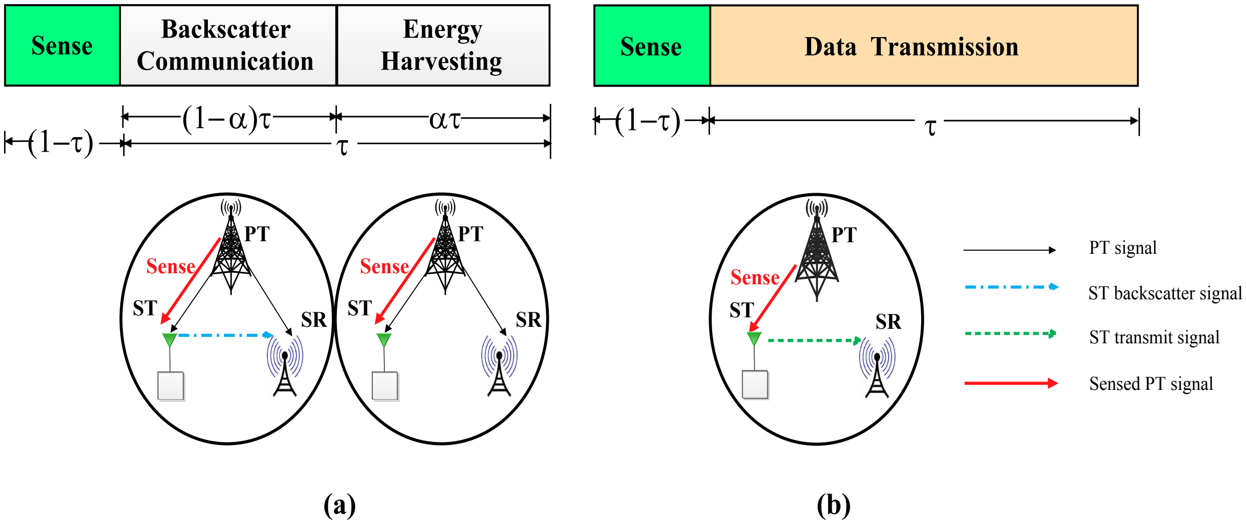

Fig. 1. Time slot structure when: (a) the PU is declared to be present; (b) when the PU is declared to be absent.

PT signal at the ST, calculated from the Friis' equation as [16] $P_R = \delta P_{T,PU} G_T G_R \lambda^2/(4\pi d)^2$,, where $\delta \in [0, 1]$ is the energy harvesting efficiency, G_T is the PT antenna gain, G_R is the ST antenna gain, λ is the wavelength of the emitted wave, and d is the distance between the PT and ST. Based on the above, it follows that

$$R_{h,S_3} = \tau\kappa W \log_2\left(1+\frac{\alpha\tau P_R - \tau P_c - P_s(1-\tau)}{[Z_I P_{T,PU} + P_0]\,\tau}\right). \quad (5)$$

S4: In this scenario, the ST correctly declares the PT to be inactive with probability $P(\mathcal{H}_0)(1 - P_f)$, and hence the CR network achieves the throughput in the HTT mode, namely

$$R_{h,S_4} = \tau W \log_2\left(1 + \frac{P_{tr}}{P_0}\right), \quad (6)$$

$$= \tau W \log_2\left(1+\frac{\alpha\tau P_R - \tau P_c - P_s(1-\tau)}{P_0}\right). \quad (7)$$

Considering the above four scenarios, the average throughput of the ABC-HTT-based CR network can be expressed as

$$R(\tau, \alpha, \varepsilon) = R_b(\tau, \alpha, \varepsilon) + R_h(\tau, \alpha, \varepsilon), \quad (8)$$

where $R_b(\tau, \alpha, \varepsilon)$ denotes the average achievable throughput of the CR network in the ABC mode, given by

$$R_b(\tau, \alpha, \varepsilon) \triangleq P(\mathcal{H}_1) P_d (1 - \alpha)\tau B_b, \quad (9)$$

whereas

$$R_h(\tau, \alpha, \varepsilon) \triangleq \kappa P(\mathcal{H}_1)(1-P_d) + \tau W \log_2\left(1+\frac{P_{tr}}{Z_I P_{T,PU} + P_0}\right) + P(\mathcal{H}_0)(1 - P_f)\tau W \log_2\left(1+\frac{P_{tr}}{P_0}\right), \quad (10)$$

denotes the average achievable throughput of the CR network in the HTT mode. It is noted that in order for the throughput to be non-negative, the harvested energy should be greater than the consumed energy. This requirement imposes the constraint: $E_h = \alpha\tau P_R \geq E_c + E_s$ i.e. $\alpha \geq (E_c + E_s)/(\tau\ P_R)$. Denoting $\alpha^\dagger \triangleq (E_c + E_s)/(\tau\ P_R)$ as the minimum energy harvesting time to obtain enough energy for the ST to operate in the HTT mode, we have the constraint that $\alpha \in [\alpha^\dagger, 1]$. In other words, $R_h(\tau, \alpha, \varepsilon) > 0$, only when $\alpha \in [\alpha^\dagger, 1]$; otherwise, $R_h(\tau, \alpha, \varepsilon) = 0$. Now, recall that P_s denotes the power required by ST to perform sensing. Thus, the average energy consumption in the CR network can be written as

$$E(\tau, \alpha, \varepsilon) = E_b(\tau, \alpha, \varepsilon) + E_h(\tau, \alpha, \varepsilon) \quad (11)$$

$$= P_s(1-\tau) + \tau P_{\text{tr}}\{P(\mathcal{H}_1)(1-P_d) + P(\mathcal{H}_0)(1-P_f)\}, \quad (12)$$

where $E_b(\tau, \alpha, \varepsilon)$ and $E_h(\tau, \alpha, \varepsilon)$ denote the energy consumed by the CR network, while operating in the ABC mode and HTT mode, respectively. In the same context, the energy efficiency of the CR network, in bits/s/Hz/J, is defined as

$$EE(\tau, \alpha, \varepsilon) \triangleq \frac{R(\tau, \alpha, \varepsilon)}{E(\tau, \alpha, \varepsilon)} = EE_b(\tau, \alpha, \varepsilon) + EE_h(\tau, \alpha, \varepsilon), \quad (13)$$

where $EE_b(\tau, \alpha, \varepsilon) \triangleq R_b(\tau, \alpha, \varepsilon)/E(\tau, \alpha, \varepsilon)$ and $EE_h(\tau, \alpha, \varepsilon) \triangleq R_h(\tau, \alpha, \varepsilon)/E(\tau, \alpha, \varepsilon)$, denote the energy efficiency values due to the ST operating in ABC and HTT modes, respectively. The constraint $\alpha \in [\alpha^\dagger, 1]$ yields the following condition on the overall energy efficiency.

$$EE(\tau, \alpha, \varepsilon) = \begin{cases} EE_b(\tau, \alpha, \varepsilon) + EE_h(\tau, \alpha, \varepsilon), & \alpha^\dagger \leq \alpha \leq 1, \\ EE_b(\tau, \alpha, \varepsilon), & \text{otherwise.} \end{cases}$$

Next, we describe an optimization problem in order to determine the optimal values of the parameters ε, α and τ, such that the energy efficiency of the CR network is maximized. To this end, we formulate the following maximization problem, subject to the interference constraint on the primary network and energy harvesting constraint:

$$\begin{aligned}\mathcal{OP}: \max_{\tau,\alpha,\varepsilon} \quad & EE(\tau,\alpha,\varepsilon) \\ \text{s.t.} \quad & P_f \le \overline{P}_f, \qquad P_d \ge \overline{P}_d, \\ & \alpha^\dagger \le \alpha \le 1, \quad 0 \le \tau \le 1, \end{aligned} \tag{14}$$

for some $\overline{P}_d, \overline{P}_f \in (0,1)$. In the next section, we provide the detailed solution of the above optimization problem.

IV. Performance Analysis

In the following theorem, we derive the optimal value of the detection threshold, ε^*, that satisfies the primary interference constraint given in problem $\mathcal{OP}$.

Theorem 1. *The optimal threshold ε^* for the problem in $\mathcal{OP}$ is obtained when the constraint $P_d \ge \overline{P}_d$ is satisfied with equality, namely*

$$\varepsilon^* = \sigma^2 \left[(\gamma+1) + \sqrt{\frac{2\gamma+1}{(1-\tau)N_s}} Q^{-1}\left[\overline{P}_d\right] \right]. \tag{15}$$

Proof. The proof is provided in Appendix A. □

In the same context, Theorem 2 allows the determination of the conditions on the backscattering communication rate, such that an optimal value of α, denoted by α^*, exists between $\alpha^\dagger$ and 1, and provides an analytic expression for α^*, when the interference from the PU is neglected. The existence of α^* can be determined similarly for the case that includes the interference term, but it yields intractable results since the derivation of a closed form solution is infeasible.

Theorem 2. *When $\alpha^\dagger \le \alpha \le 1$, the backscatter transmission rate $B_b \in \left(B_{b,LB} = g(1), B_{b,UB} = g(\alpha^\dagger)\right)$, where*

$$g(\alpha) \triangleq \frac{P(\mathcal{H}_0)}{P(\mathcal{H}_1)} \frac{(1-P_f)}{P_d \ln 2} \frac{\tau W \tau P_R}{(P_0 - P_c)\tau + P_s(1-\tau) + \alpha\tau P_R} \tag{16}$$

and the interference from the PU is neglected, then, there exists an optimal solution $\alpha^* \in [\alpha^\dagger, 1]$, which is expressed as

$$\alpha^* = \left(\frac{P(\mathcal{H}_0)(1-P_f)\tau W}{P(\mathcal{H}_1)P_d \ln 2}\right) - \left(\frac{(P_0+P_c)\tau + P_s(1-\tau)}{\tau P_R}\right). \tag{17}$$

Proof. The proof is provided in Appendix B. □

Once ε^* and α^* are determined, we need to determine the optimal τ, denoted by τ^*, which accounts for the data transmission duration. The function $EE(\tau,\alpha^*,\varepsilon^*)$ is concave in τ.[1] Thus, τ^* can be determined by standard methods, such as steepest gradient techniques. Based on the above, the maximum energy efficiency is evaluated as:

$$\begin{aligned} & EE_{\max}(\tau^*,\alpha^*,\varepsilon^*) \\ &= \begin{cases} \max\left[EE_b(\tau^*,0,\varepsilon^*), \right. \\ \quad \left. EE_b(\tau^*,\alpha^*,\varepsilon^*) + EE_h(\tau^*,\alpha^*,\varepsilon^*)\right], & \alpha^\dagger \le \alpha^* \le 1, \\ EE_b(\tau^*,0,\varepsilon^*), & \text{otherwise.} \end{cases} \end{aligned} \tag{18}$$

[1]The proof is omitted due to lack of space.

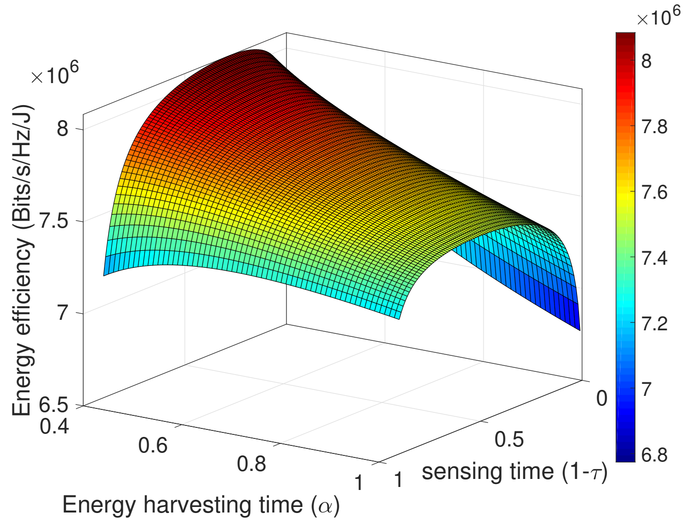

Fig. 2. Variation of energy efficiency with α and τ, for ε^* in (15). Energy efficiency is concave in both α and τ.

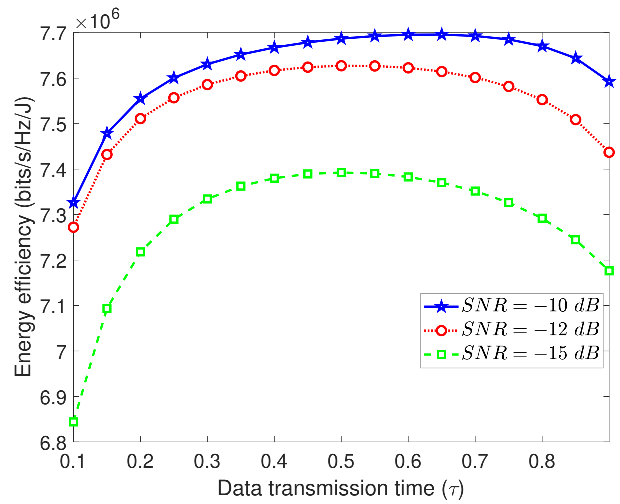

Fig. 3. Variation of the energy efficiency $EE(\tau,\alpha^*,\varepsilon^*)$ with the data transmission time, τ, for different SNR values.

V. Numerical Results

In this section, we present the corresponding numerical results on the performance of the ABC-HTT-based CR network. In particular, we consider the following parameters: the target probability of detection, $\overline{P}_d$, and false-alarm probability, $\overline{P}_f$, are set to 0.9 and 0.1, respectively [13], whereas the prior probabilities $P(\mathcal{H}_0)$ and $P(\mathcal{H}_1)$ are set to 0.75 and 0.25, respectively. The signal bandwidth and the transmitted power are set to 6 MHz, and 17 kW, respectively [7]. Also, without a loss of generality and unless stated otherwise, we assume the following values: The number of observations is 2000, $B_b = 50 \times 10^3$ bps, SNR = -10 dB, $\kappa = 1$, $P_s = 1$ mW, $P_c = 0.1$ mW, $\delta = 0.6$, the distance d in the Friis' equation is chosen such that $P_R = 0.25$ W, and the path loss and other impairments due to primary interference as 0.5×10^{-3}.

Figure 2 shows the variation of the EE with respect to the

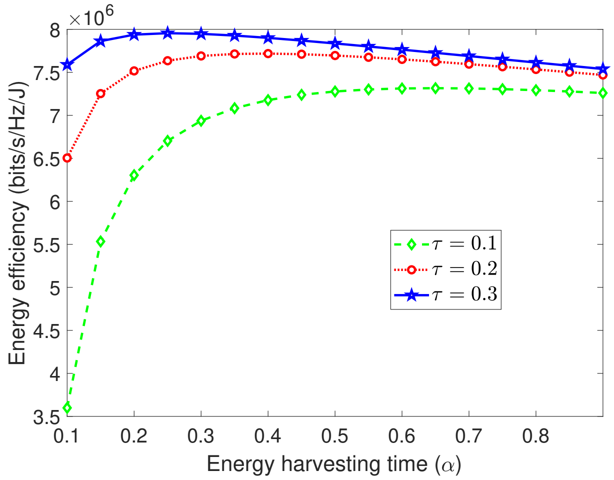

Fig. 4. Variation of the energy efficiency $EE(\tau, \alpha^*, \varepsilon^*)$ with α, for different values of τ.

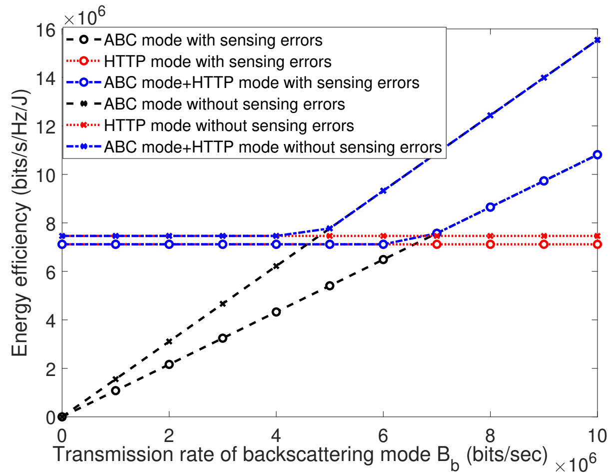

Fig. 5. Effect of sensing errors on the optimal energy efficiency. Combining ABC and HTT modes yields a higher overall energy efficiency.

parameters α and τ, with ε^* chosen according to (15). The sampling frequency is chosen such that the number of samples is 1000, and the sensing power $P_s = 0.3$ mW. Also, we set $\kappa = 0.6$, and $\delta = 0.6$. It is evident that the EE is concave with respect to both α and τ. Also, for a small value of α, the EE is also small since the throughput decreases due to the small energy harvesting activity. However, if ST harvests more energy, i.e., if α increases, the EE further decreases since the backscattering communication is not efficiently utilized.

Figure 3 illustrates the variation of the value of $EE(\tau, \alpha^*, \varepsilon^*)$ with τ for different SNR values. As expected, both the optimum EE and τ^* increase with SNR, since a larger SNR results in lower sensing time required to satisfy the primary interference constraints, leading to a higher data transmission time. Similarly, Figure 4 demonstrates the variation of the value of $EE(\tau, \alpha, \varepsilon^*)$ for different values of τ. It is evident that the optimal α^* exists for each τ, and it decreases with an increase in τ, as indicated in (17). Moreover, it is intuitive to note that as τ increases, EE also increases.

Finally, Figure 5 illustrates the effect of sensing errors on the performance of the ABC-HTT-based CR network. In order to calculate the performance of the system without sensing errors, we follow the procedure similar to that described in [7]. By choosing the indicative values $N_s = 2000$, and $P_R = 1$ W, it is shown that the optimal EE achieved with no sensing errors is, as expected, higher than the realistic case with present sensing errors. Additionally, we observe that EE increases in both cases, due to the use of both ABC and HTT modes. That is, the energy efficiency achieved due to only ABC or HTT mode is lower than that obtained by combining the two modes, in both the presence and absence of sensing errors.

VI. Conclusion

We investigated the performance of ABC-HTT-based CRNs in the presence of sensing errors. We derived novel analytic expressions for the average achievable throughput, average energy consumption and EE of the considered network. Then, we formulated an optimization problem that maximizes the EE of the ABC-HTT-CRN, for a given set of constraints including the primary interference constraint. Finally, we derived the optimal set of parameters that maximize the EE of the proposed network. The offered results provided interesting theoretical and technical insights on the behavior of ABC systems that are expected to be useful in the design and deployment of future systems in various wireless applications of interest.

VII. Appendix

A. Proof of Theorem 1

To show that $P_d \geq \overline{P}_d$ is satisfied with equality, it is sufficient to show $\partial EE(\tau, \alpha, \varepsilon)/\partial \varepsilon \geq 0$, for all ε. With some algebraic manipulations, it can be shown that

$$\begin{aligned}\frac{\partial EE(\tau,\alpha,\varepsilon)}{\partial\varepsilon} &= \frac{\partial P_d}{\partial\varepsilon}\frac{P(\mathcal{H}_1)(1-\alpha)\tau B_b}{E(\tau,\alpha,\varepsilon)} \\ &- \frac{\partial P_d}{\partial\varepsilon}P(\mathcal{H}_1)\kappa\tau W\log_2\left(1+\frac{P_{tr}}{Z_I P_{T,PU}+P_0}\right) \\ &+ \frac{R(\tau,\alpha,\varepsilon)}{E^2(\tau,\alpha,\varepsilon)}\left\{\frac{\partial P_d}{\partial\varepsilon}\tau P_{tr}P(\mathcal{H}_1)\right. \\ &\left.-\frac{\partial P_f}{\partial\varepsilon}\left[P(\mathcal{H}_0)\tau W\log_2\left(1+\frac{P_{tr}}{P_0}\right)+\tau P_{tr}P(\mathcal{H}_0)\right]\right\}. \end{aligned} \quad (19)$$

In addition, it is noted that

$$\frac{\partial P_f}{\partial\varepsilon} = -\exp\left[-\frac{(1-\tau)N_s(\frac{\epsilon}{\sigma^2}-1)^2}{2}\right]\frac{\sqrt{N_s(1-\tau)}}{\sqrt{2\pi\sigma^2}} \leq 0$$

and

$$\frac{\partial P_d}{\partial\varepsilon} = -\exp\left[-\frac{(1-\tau)N_s(\frac{\epsilon}{\sigma^2}-\gamma-1)^2}{2(1+2\gamma)}\right]\frac{\sqrt{\frac{N_s(1-\tau)}{1+2\gamma}}}{\sqrt{2\pi\sigma^2}} \leq 0,$$

with $\partial P_d/\partial\varepsilon \geq \partial P_f/\partial\varepsilon$. Following these results, equation (19) can be simplified and shown to be non-negative if

$$\begin{aligned} &P(\mathcal{H}_1)\kappa\tau W\log_2\left(1+\frac{P_{tr}}{Z_I P_{T,PU}+P_0}\right) \\ &-\frac{1}{E}P(\mathcal{H}_1)(1-\alpha)\tau B_b - \tau P_{tr}P(\mathcal{H}_1)\frac{R}{E^2} > 0. \end{aligned} \quad (20)$$

To this effect, it is readily verified that the above requirement holds when W and P_{tr} are selected such that

$$W\kappa \log\left(1+\frac{P_{tr}}{P_0}\right) \geq \frac{1}{E}(1-\alpha)B_b + P_{tr}\frac{R}{E^2}, \qquad (21)$$

in which case, $\partial EE/\partial \varepsilon \geq 0$, for all ε. Hence, it is sufficient to choose the value of ε when $P_d = \overline{P}_d$ is satisfied.

B. Proof of Theorem 2

Let us define the following positive constants

$$y_1 \triangleq 1 - \frac{P_c\tau}{[Z_I P_{T,PU} + P_0]\,\tau}, \qquad (22)$$

$$y_2 \triangleq \frac{\tau P_R - P_s(1-\tau)}{[Z_I P_{T,PU} + P_0]\,\tau}, \qquad (23)$$

$$y_3 \triangleq 1 - \frac{P_c}{P_0} - \frac{P_s(1-\tau)}{P_0\tau} \qquad (24)$$

and

$$y_4 \triangleq \tau P_R/(P_0\tau). \qquad (25)$$

Then, the energy efficiency is given by

$$\begin{aligned} EE(\tau,\alpha,\varepsilon^*) = &\frac{P(\mathcal{H}_1)P_d(1-\alpha)\tau B_b}{E(\tau,\alpha,\varepsilon^*)} \\ &+ \frac{P(\mathcal{H}_1)(1-P_d)\kappa\tau W \log_2[y_1+\alpha y_2]}{E(\tau,\alpha,\varepsilon^*)} \\ &+ \frac{P(\mathcal{H}_0)(1-P_f)\tau W \log_2[y_3+\alpha y_4]}{E(\tau,\alpha,\varepsilon^*)}. \end{aligned} \qquad (26)$$

Now, consider $\partial EE(\tau,\alpha,\varepsilon^*)/\partial\alpha$, which is given by

$$\begin{aligned} \frac{\partial EE(\tau,\alpha,\varepsilon^*)}{\partial\alpha} = &\frac{P(\mathcal{H}_1)(1-P_d)\kappa\frac{\tau W}{\ln 2}\frac{y_2}{y_1+\alpha y_2}}{E(\tau,\alpha,\varepsilon^*)} \\ &- \frac{P(\mathcal{H}_1)P_d\tau B_b}{E(\tau,\alpha,\varepsilon^*)} + \frac{P(\mathcal{H}_0)(1-P_f)\frac{\tau W}{\ln 2}\frac{y_3}{y_1+\alpha y_4}}{E(\tau,\alpha,\varepsilon^*)} \end{aligned} \qquad (27)$$

while the second derivative of $EE(\tau,\alpha,\varepsilon^*)$ is

$$\begin{aligned} \frac{\partial^2 EE(\tau,\alpha,\varepsilon^*)}{\partial\alpha^2} &= \frac{\partial^2 EE_h(\tau,\alpha,\varepsilon^*)}{\partial\alpha^2} \\ &= -\frac{P(\mathcal{H}_1(1-P_d)\kappa}{E}\frac{\tau W}{\ln 2}\frac{y_2^2}{(y_1+\alpha y_2)^2} \\ &\quad - \frac{P(\mathcal{H}_0)(1-P_f)}{E}\frac{\tau W}{\ln 2}\frac{y_4^2}{(y_1+\alpha y_2)^2} < 0. \end{aligned} \qquad (28)$$

From (27) and (28), we can infer that $\partial EE(\tau,\alpha,\varepsilon^*)/\partial\alpha$ is a decreasing function of α. Furthermore, to guarantee that there exist a value of $\alpha \in [\alpha^\dagger, 1]$ such that $EE'_{ABC}(\tau,\alpha,\varepsilon^*) = 0$, we calculate the following boundary values. To this effect, observing that when $\alpha = \alpha^\dagger$, it follows that $\partial EE(\tau,\alpha^\dagger,\varepsilon^*)/\partial\alpha \geq 0$, whereas when $\alpha = 1$, we get $\partial EE(\tau,\alpha^\dagger,\varepsilon^*)/\partial\alpha \leq 0$. Therefore, there exists an $\alpha^* \in [\alpha^\dagger, 1]$ where the derivative $\partial EE(\tau,\alpha^\dagger,\varepsilon^*)/\partial\alpha$ is exactly 0. Thus, the bounds on B_b are obtained by equating the expression in (27) to zero, and rearranging accordingly. If the effective interference from the PU is neglected, then $B_b = g(\alpha)$. Now, the upper and lower bounds on B_b, namely, $B_{b,LB}$ and $B_{b,UB}$ can be obtained by substituting for the value of α corresponding to the two extreme cases 1 and $\alpha^\dagger$, respectively. These bounds are as given in Theorem 2. Therefore, when $B_b \in (B_{b,LB}, B_{b,UB})$, $EE(\tau,\alpha,\varepsilon^*)$ is concave in α. Finally, the optimal $\alpha^* \in [\alpha^\dagger, 1]$, can be obtained by neglecting the interference term and equating the first derivative to zero, which is expressed as α^* in Theorem 2.

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