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Energy Efficiency Optimization for NOMA-Based Cognitive Radio With Energy Harvesting

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ABSTRACT Energy Efficiency (EE) is a significant problem for Cognitive Radio (CR) network. Recently, more interest has focused on EE optimization problem in wireless-powered communication. In conventional CR network, spectrum sensing and limited battery capacity may decrease system performance. In this article, a Non-Orthogonal Multiple Access (NOMA) system with Simultaneous Wireless Information and Power Transfer (SWIPT) for CR network is studied. The frame structure is designed with two subslots. In the downlink subslot, the Secondary Users (SUs) harvest wireless energy from Radio Frequency (RF) signals and sense the spectrum state simultaneously. In the uplink subslot, SUs transmit their independent information to Base Station (BS). Two modes are considered in this article: overlay network and underlay network. A CR-NOMA system model is presented and the approximate expressions of EE for two modes are obtained. Based on the subslot allocation, two optimization problems aiming to maximize EE are formulated. In the overlay network, the constraints are transmit power and total transmission slot. In the underlay network, instead of sensing the spectrum, SUs utilize the channel with primary user (PU) simultaneously. Thus, the constraints of interference threshold and channel gain of PU are also taken into considered. The proposed optimization problems can be regarded as nonlinear fractional programming. The Dinkelbach method is used to transform the nonlinear fractional programming problems into the parametric ones. Simulation results show that there indeed exists a best downlink subslot to maximize the EE of CR-NOMA networks.

INDEX TERMS Cognitive radio, NOMA, energy efficiency maximization, energy harvesting, subslot allocation.

I. INTRODUCTION

Cognitive Radio (CR) can effectively alleviate spectrum resource shortage by performing opportunistic spectrum access in time, frequency and airspace [1]–[5]. When the Primary User (PU) is absent, CR allows the Secondary Users (SUs) to access idle channel to improve the spectrum utilization. Since PU has the priority to use the licensed frequency band, the SUs must detect the licensed frequency band occupancy in real time via spectrum sensing [6], [7]. Energy detection is widely used to perform spectrum sensing currently because it is easily implemented and no PU's prior information is required. However, sensing performance may suffer from the effects of hidden terminal problems [8], [9] such as shadow effect and multipath fading. Two main modes, i.e., overlay CR network and underlay CR network, have

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been widely studied in current researches. For the former, the SUs can utilize the frequency band released by PU so that the conflict with the PU's information transmission can be avoided. For the latter, the SUs can utilize the frequency band with PU as long as the interference with PU is limited below a certain threshold.

Non-Orthogonal Multiple Access (NOMA) [10]–[13] is a promising wireless access technique for the coming 5G era. NOMA uses non-orthogonal transmission at the transmitter and users' information is superposed in power domain for higher spectrum efficiency. Different from Orthogonal Multiple Access (OMA), NOMA can serve multiple terminals over the same resource block, thus it can effectively enhance sum rate. Successive Interference Cancellation (SIC) is adopted to decode the users' information at the receiver. Specifically, the user with the best channel condition is decoded firstly, while other users are regarded as interference. Reference [14] gave the review on NOMA and compared OFDMA and NOMA. Specifically, OFDMA is applied to Long Term Evolution (LTE) radio access scheme, while NOMA is applied to 5G communication system. NOMA can improve Spectrum Efficiency (SE) due to non-orthogonal transmission and SIC, thus the application of NOMA to CR secondary network is necessary to improve the SE in CR network. Reference [15] designed a CR-NOMA model and an SE optimization problem was solved by optimizing the sensing subslot. Since CR-NOMA combines the advantages of both the techniques, it is considered as a promising technique for the coming 5G communication system [16], [17].

Recently, Simultaneous Wireless Information and Power Transfer (SWIPT) [18]–[21] has been regarded as a promising solution to energy-limited wireless communication networks. From the perspective of information and energy transmission, SWIPT can effectively balance information transmission in the uplink and energy harvesting in the downlink. Thus, there are numerous research efforts to the optimization of uplink and downlink transmission subslot allocation in most existing literature. Actually, Radio Frequency (RF) signals at the receiver can be divided into two streams: one stream is used to harvest energy, while the other one is used to transmit information [22]. However, due to the practical circuit limitation, it is not realizable to perform energy harvesting and information decoding simultaneously at the receiver. In order to deal with the problem, Power Splitting (PS) and Time Switching (TS) mode were proposed [23]. The harvested energy can be used for information transmission and circuit power consumption so that the lifetime of wireless devices can be prolonged.

With the development of 5G communication system, massive device access and increasing energy consumption have drawn the attention of academia and industry to Energy Efficiency (EE). Thus, EE optimization becomes an important problem to be investigated from a green communication perspective. EE is defined as the energy consumed per bit of information transmitted, which is equals to the power consumption for one bit information transmission. Several wireless communication system models focusing on EE optimization have been proposed in recent researches. A multi-hop decode and forward relay CR sensor network was proposed in [24] to maximize EE by optimizing sensing subslot and power allocation. In [25], the EE optimization of Orthogonal Frequency Division Multiplexing Access (OFDMA) system was investigated by jointly optimizing the subcarrier and power allocation. In [26], the relationship between user matching and power allocation was discussed to maximize EE considering the constraints of load balance, users' QoS requirement and cross-tier interference. An EE optimization problem for the Urban Integrated Energy Systems (UIES) was proposed in [27] and the external point method was applied to solve the optimization problem. Reference [28] studied the impacts of transceiver impairments for coordinated transmission in Private Time Division LTE (Private TD-LTE) wireless network. Then, an optimization problem and the corresponding solving algorithm based on Langrange Multiplier method were proposed to maximize the minimum EE. In addition, the joint optimization of EE and SE has been studied because the wireless networks pursue both high throughput and low power consumption. In [29], a joint EE and SE optimization problem was investigated by optimizing the sensing subslot and the final decision threshold.

In recent researches, the EE optimization for SWIPT based wireless communication networks has attracted great interest. Reference [30] investigated the EE optimization problem of SWIPT based Multiple Input Multiple Output (MIMO) system, and focused on the covariance of Channel State Information (CSI) feedback to obtain the improvement of system capacity. In [31], a resource allocation scheme was studied for SWIPT based CR network to maximize the throughput of secondary network and the harvested energy. Wherein, the tradeoff between sensing performance and EE was achieved. In [32], an optimal resource allocation strategy for SWIPT based networks to maximize EE was proposed considering channel estimation by determining the proper training sequence. An optimal resource allocation algorithm was proposed in [33], [34] for SWIPT based Multiple Input Single Output (MISO) system under the constraints of channel fading and transmit power. In [35], a distributed iterative algorithm for power allocation and relay node selection scheme was proposed to optimize the performance of cooperative transmission wireless relay CR network.

The EE optimization for CR-NOMA network is also widely studied in recently works. In [36], an EE optimization problem for CR-NOMA network was proposed subject to a QoS constraint for each PU. Then, an algorithm using Sequential Convex Approximation (SCA) method was proposed to solve the non-convex fractional programming problem. In [37], a CR-NOMA system model was presented to maximize the minimum secrecy EE considering the practical nonlinear energy harvesting and information security simultaneously. Reference [38] focused on the EE optimization for NOMA based heterogeneous cloud CR network and elaborated promising 5G technologies such as massive

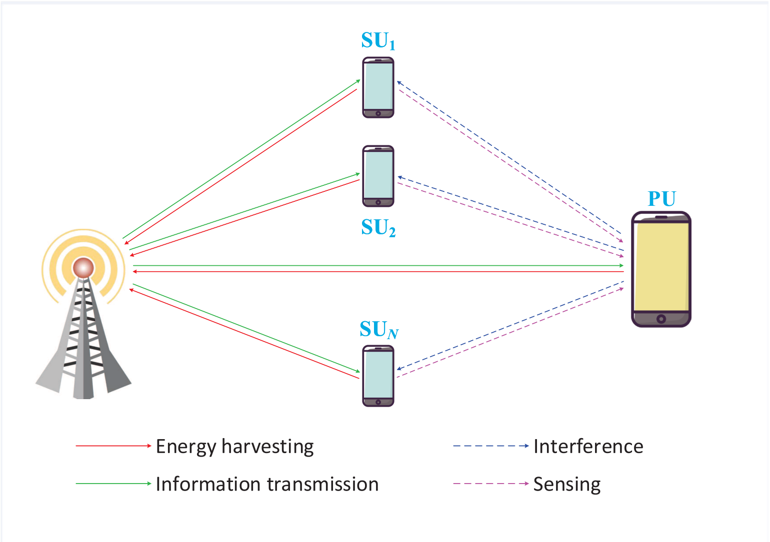

FIGURE 1. **System model of CR-NOMA.**

MIMO, millimeter-wave communications and Device-to-Device (D2D) communications. In [39], an EE optimization problem was investigated for a relay assisted CR-NOMA network subject to the total transmit power and QoS of SUs. Since the optimization problem is non-convex, the Lagrange dual algorithm based on the first-order Taylor expansion was proposed to solve it.

According to the literature reviews above, though there are some works on SWIPT and CR-NOMA network, the research on EE for such network can still be further improved. Therefore, considering two CR networks modes, a SWIPT based CR-NOMA system model is proposed in this article to improve EE. On one hand, different from the traditional CR network, CR-NOMA can achieve higher SE and information rate. On the other hand, SWIPT can achieve the best tradeoff between information and lifetime for energy-limited wireless networks. The contributions of this article are summarized as follows:

- A SWIPT based CR-NOMA system model combined overlay mode and underlay mode is proposed. On one hand, due to the non-orthogonality, since NOMA can hold multiple users on one subcarrier, the SE can be improved. On the other hand, since SWIPT requires users to harvest energy from wireless signals, the EE can be improved. Therefore, the proposed SWIPT based CR-NOMA model can combine CR with the advantages of NOMA and SWIPT.
- Two EE optimization problems based on downlink subslot allocation are proposed under the constraints of total transmission slot, downlink transmit power, interference threshold and channel gain of PU. Specifically, the convexity of system sum rate is proved so that the EE can be regarded as a pseudo-concave function of the downlink subslot. The concrete expressions of EE are derived for two network modes whose convexity is also proved.
- An iterative algorithm based on the Dinkelbach method is proposed to solve the proposed optimization problems. The proposed optimization problems with fractional objective function are transformed into the parametric ones. Simulation results show the tradeoffs between EE and other parameters such as downlink subslot, total transmit power and channel gain of PU.

The rest of the article is organized as follows. In Section II, the system model is proposed, and two modes including overlay network and underlay network are taken into consideration. In Section III, the EE optimization problems for two modes are formulated, and then an iterative algorithm is proposed. The simulation results and discussions are presented in Section IV. Finally, Section V concludes this article.

II. SYSTEM MODEL

A. OVERLAY CR NETWORK

In this section, a SWIPT based CR-NOMA system model consisting of one BS, one PU and N SUs is proposed as shown in Fig. 1. The notation of necessary parameters is listed in Table 1. In the proposed model, PU and SUs harvest energy first, then transmit independent information to BS. Furthermore, SUs perform spectrum sensing which may produce interference with PU's information transmission. Fig. 2 shows the frame structure of the overlay CR-NOMA network. T is the duration of one frame which is called transmission slot and the frame is divided into two subslots: downlink subslot τ is used for spectrum sensing and SWIPT, while uplink subslot $T-\tau$ is used for transmitting SUs' data. Here, SWIPT means that PU and SUs harvest energy and PU transmits its information simultaneously.

TABLE 1. System parameters.

Parameters	Variable
Downlink subslot	τ
Probability of detection	P_d
Probability of false alarm	P_f
Probability of PU existence	PH_0
Complementary distribution function	$Q(x)$
Achievable rate of i-th user	$R_i(\tau)$
Sum rate of overlay NOMA secondary network	$R(\tau)$
Sum rate of underlay NOMA secondary network	$R^{'}(\tau)$
Sum rate of overlay CR-NOMA network	K_4
Downlink transmit power	P_a
Transmit power of PU	P_s
Channel gain of PU	g_s
Interference threshold	I_{max}

NOMA is applied to secondary CR network during the uplink information transmission subslot. In the downlink subslot τ, the transmit power of the *i-th*, $i = 1, 2, \ldots N$ user can be expressed as

$$P_i = \frac{g_i P_a \tau}{1-\tau} \tag{1}$$

where g_i denotes the power gain between the *i-th* user and BS, while P_a denotes the downlink transmit power. h_i, $i = 1, 2, \ldots N$ denotes the channel coefficient and assume that $|h_1| > |h_2| > \cdots > |h_N|$. Thus, the achievable rate of the *i-th* user can be expressed as

$$R_i(\tau) = (1-\tau)\log_2\left(1 + \frac{\gamma_i}{1 + \sum\limits_{j=i+1}^{N} \gamma_j}\right) \tag{2}$$

where $\gamma_i = |h_i|^2 P_i$ denotes the normalized Signal to Noise Ratio (SNR) of the *i-th* user. Substituting (1) into (2), and we have

$$R_i(\tau) = (1-\tau)\log_2\left(1 + \frac{\alpha_i \tau}{1 - \tau + \sum\limits_{j=i+1}^{N} \alpha_j \tau}\right) \tag{3}$$

where $\alpha_i = g_i |h_i|^2 P_a$. Thus, the sum rate of overlay NOMA secondary network can be expressed as

$$R(\tau) = (1-\tau)\log_2\left(1 + \sum_{i=1}^{N} \alpha_i \frac{\tau}{1-\tau}\right) \tag{4}$$

In the overlay mode, SUs need to detect the PU's licensed spectrum periodically. During the spectrum sensing, BS receives the PU's radio signal independently and the received signal $y(t)$ can be denoted as

$$y(t) = \begin{cases} n(t) & H_0, \\ h^{ps} s(t) + n(t) & H_1, \end{cases} \tag{5}$$

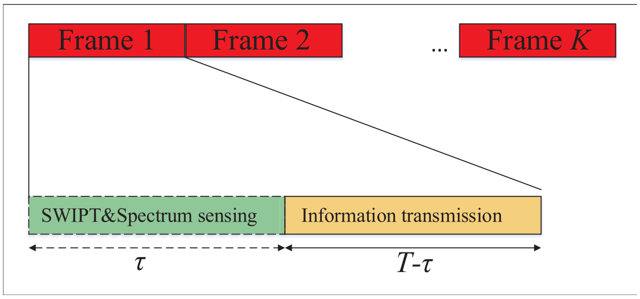

FIGURE 2. Frame structure of overlay CR-NOMA.

where H_0 and H_1 represent the idle and busy state of PU, respectively. $s(t)$ denotes the PU's radio signal with transmit power P_s, h^{ps} denotes the channel gain between PU's transmitter and SU's receiver, and $n(t)$ is a Gaussian, independent and identically distributed random process with mean zero and variance σ^2. $M = \tau f_s$ is defined as the sampling quality where f_s is the sampling frequency. Energy detection method is applied to perform spectrum sensing and the energy statistics $\phi(y)$ of

$$\phi(y) = \frac{1}{M}\sum_{i=1}^{M} |y(t)|^2 \tag{6}$$

The probability of detection P_d is the probability that the network will correctly judge the presence of PU when PU exists. The probability of false alarm P_f is the probability that the network judge the presence of PU when PU does not exist. The P_d and P_f can be respectively expressed as

$$\begin{cases} P_f = Q\left(\left(\dfrac{\lambda}{\sigma^2} - 1\right)(\tau f_s)^{1/2}\right) \\ P_d = Q\left(\left(\dfrac{\lambda}{\sigma^2} - \gamma_i - 1\right)\left(\dfrac{\tau f_s}{2\gamma_i + 1}\right)\right) \end{cases} \tag{7}$$

where $\gamma_i = \frac{1}{N}\sum\limits_{i=1}^{N}\left(P_s |h_{ij}^{ps}|^2/\sigma^2\right)$ denotes the sensing SNR of the *i-th* user on the licensed channel j, h_{ij}^{ps} denotes the sensing channel gain between PU's transmitter and SU's receiver, N denotes the quality of SUs and λ denotes the decision threshold. $Q(.)$ is the complementary distribution function of the standard Gaussian, i.e.,

$$Q(x) = \frac{1}{(2\pi)^{1/2}}\int_x^{\infty} \exp\left(-\frac{t^2}{2}\right)dt \tag{8}$$

Here $\bar{P}_d$ represents the target P_d and $\bar{P}_f$ represents the target P_f. For a certain $\bar{P}_d$ or $\bar{P}_f$, the expressions of P_d and P_f are respectively presented as

$$\begin{cases} P_f = Q\left(\sqrt{2\gamma_i + 1} Q^{-1}\left(\bar{P}_d\right) + \sqrt{\tau f_s}\gamma_i\right) \\ P_d = Q\left(\dfrac{1}{\sqrt{2\gamma_i + 1}}\left(Q^{-1}(\bar{P}_f) - \sqrt{\tau f_s}\gamma_i\right)\right) \end{cases} \tag{9}$$

$P(H_1)$ and $P(H_0)$ are defined as the probabilities of the presence and absence of PU, respectively, thus

$P(H_1) + P(H_0) = 1$. In traditional CR network, there are four possible cases:

- The PU is present and the network correctly detects the presence of PU. The probability of this situation is $P(H_1)(1 - P_f)$. In this case, since SUs can not utilize the channel to transmit information, the sum rate of CR network $K_1 = 0$ during one slot.
- The PU is present but the network falsely detects the presence of PU. The probability of this situation is $P(H_1)(1 - P_d)$. In this case, PU and SUs utilize the channel to transmit information simultaneously. Since PU has a high priority, the sum rate of CR network $K_2 = 0$ during one slot.
- The PU is absent and the network falsely detects the presence of PU. The probability of this situation is $P(H_0)P_f$. In this case, since SUs don't utilize the channel to transmit data, the sum rate of CR network $K_3 = 0$ during one slot.
- The PU is absent and the network correctly detects the absence of PU. The probability of this situation is $P(H_0)(1 - P_f)$. In this case, SUs utilize the channel to transmit information and the sum rate of CR network can be denoted as K_4.

We mainly focus on the fourth case. Based on NOMA secondary network, the sum rate of overlay CR-NOMA network K_4 can be given as

$$K_4 = R(\tau) P(H_0) \left(1 - P_f\right) \tag{10}$$

First, we substitute (9) into (10) and choose a proper $\bar{P}_d$. Thus, we have

$$K_4 = R(\tau) P(H_0) \left(1 - Q\left(\alpha + \sqrt{\tau f_s \gamma}\right)\right) \tag{11}$$

where, $\alpha = \sqrt{2\gamma_i + 1} Q^{-1}\left(\bar{P}_d\right)$.

Then, we substitute (4) into (11) and the K_4 expression can be given as (12), as shown at the bottom of this page. Obviously, K_4 is the function of downlink subslot τ.

Therefore, the EE of CR-NOMA overlay network is denoted as the ratio of sum rate to the energy consumption, i.e.,

$$EE(\tau) = \frac{R(\tau) P(H_0) \left(1 - Q(\alpha + \sqrt{\tau f_s \gamma})\right)}{\tau(P_{SS} + P_{CD}) + (1 - \tau)P_{CU}} \tag{13}$$

where, P_{SS} denotes the sensing power during the downlink subslot τ, and P_{CU} denotes the power consumption for decoding information at the receiver during the uplink subslot $T - \tau$. P_{CD} denotes the circuit power consumption during the downlink subslot τ, while the users' circuit power consumption during the uplink subslot $T - \tau$ is supplied by the harvested energy. Here we don't consider extra power consumption.

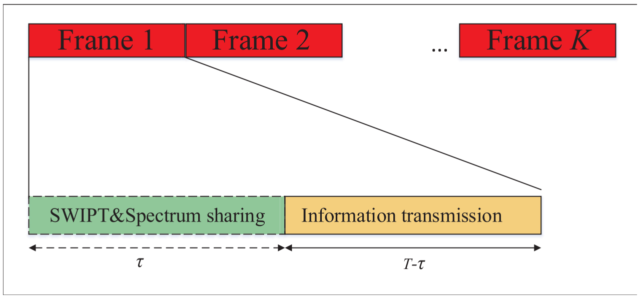

FIGURE 3. Frame structure of underlay CR-NOMA.

B. UNDERLAY CR NETWORK

In underlay CR-NOMA network, since SUs no longer sense the channel state, SUs and PU utilize the channel to transmit information simultaneously. I_{max} denotes the maximum interference threshold to PU due to the SUs' information transmission, and g_s denotes the channel gain of PU. The frame structure of underlay CR-NOMA is shown as Fig. 3.

Similarly, the sum rate of underlay NOMA secondary network can be expressed as

$$R'(\tau) = (1 - \tau) \log_2 \left(1 + \frac{\gamma_i}{P_s g_s + \sum_{j=i+1}^{N} \gamma_j}\right) \tag{14}$$

III. SYSTEM ENERGY EFFICIENCY OPTIMIZATION

A. OPTIMIZATION IN OVERLAY CR-NOMA NETWORK

In this section, the EE optimization problems focusing on the subslot allocation are formulated. In the overlay mode, the optimization problem can be formulated as

$$\begin{aligned} &\max EE(\tau) = \frac{R(\tau) P(H_0) \left(1 - Q(\alpha + \sqrt{\tau f_s \gamma})\right)}{\tau(P_{SS} + P_{CD}) + (1 - \tau)P_{CU}} \\ &s.t.\ 0 < \tau < 1 \end{aligned} \tag{15}$$

The Dinkelbach method is used to solve fractional optimization problem. First, we discuss the general optimization problem as

$$\begin{aligned} &\max \frac{A(x)}{B(x)} \\ &s.t.\ x \in S \end{aligned} \tag{16}$$

According to the Dinkelbach method, (16) can be rewritten as

$$\begin{aligned} &\max A(x) - qB(x) \\ &s.t.\ x \in S \end{aligned} \tag{17}$$

By this way, the fractional optimization problem (16) is transformed into q parameter optimization problem.

$$K_4 = P(H_0)(1 - \tau)\log_2 \left(1 + \sum_{i=1}^{N} \alpha_i \frac{\tau}{1 - \tau}\right) \left(1 - Q(\alpha + \sqrt{\tau f_s \gamma})\right). \tag{12}$$

Dinkelbach Method: $q^* = A(x^*)/B(x^*) = \max\{A(x)/B(x)|x \in S\}$, if and only if $\max\{A(x) - q^*B(x)|x \in S\} = A(x^*) - q^*B(x^*) = 0$.

To solve the proposed optimization problem, we give the following proposition.

*Proposition*1: The numerator of objective function given in (15) is concave in the interval of (τ_0,1).

Proof: Firstly we rewrite (3) as the following form

$$R_i(\tau) = (1-\tau)\log_2\left(1 + \frac{\alpha_i\tau}{1+\omega_i\tau}\right) \tag{18}$$

where, $\omega_i = -1 + \sum_{j=i+1}^{N} \alpha_j$.

Then, the first partial derivative of (18) with respect to τ is given as

$$\begin{aligned}\frac{\partial R_i(\tau)}{\partial\tau} &= -\log_2(1 + \frac{\alpha_i\tau}{1+\omega_i\tau}) \\ &\quad + \frac{(1-\tau)\alpha_i}{(1+\omega_i\tau+\alpha_i\tau)(1+\omega_i\tau)}\end{aligned} \tag{19}$$

Next, the second partial derivative of (18) with respect to τ is given as

$$\begin{aligned}&\frac{\partial^2 R_i(\tau)}{\partial\tau^2} \\ &= -\alpha_i\left[\frac{(1+\omega_i\tau+\alpha_i\tau)(2+2\omega_i\tau+2\omega_i)+(1-\tau)\alpha_i}{(1+\omega_i\tau+\alpha_i\tau)^2(1+\omega_i\tau)^2}\right]\end{aligned} \tag{20}$$

According to the discussion above, $\omega_i \geq -1$ and $\alpha_i > 0$. It is obvious that $\frac{\partial^2 R_i(\tau)}{\partial\tau^2} < 0$, thus $R_i(\tau)$ is a concave function. Using the fact that concavity is preserved under summation, thus the sum rate of overlay NOMA secondary network $R(\tau)$ is concave as well. Next we prove the concavity of the numerator of objective function.

The second partial derivative of (11) with respect to τ is given as

$$\begin{aligned}\frac{\partial^2 K_4}{\partial\tau^2} &= P(H_0)\frac{\partial^2 R_i(\tau)}{\partial\tau^2}\left(1 - Q(\alpha + \sqrt{\tau f_s}\gamma)\right) \\ &\quad +2\frac{\delta R_i(\tau)}{\delta\tau} + \beta\end{aligned} \tag{21}$$

where

$$\begin{aligned}\beta &= -\frac{1}{2}\tau^{-1}\exp(-\frac{(\alpha+\sqrt{\tau f_s}\gamma)^2}{2})(\tau^{-\frac{1}{2}} + (\alpha+\sqrt{\tau f_s}\gamma)) < 0 \\ &\quad \times \left(1 - Q(\alpha + \sqrt{\tau f_s}\gamma)\right) > 0\end{aligned} \tag{22}$$

From the discussion above we can know that $\frac{\partial^2 R_i(\tau)}{\partial\tau^2} < 0$, thus the first derivative $\frac{\partial R_i(\tau)}{\partial\tau}$ is monotonically decreasing with respect to τ. Let τ_0 denote the value that makes $\frac{\partial R_i(\tau)}{\partial\tau}$ equal to zero. When $\tau \in (\tau_0, 1)$, $\frac{\partial R_i(\tau)}{\partial\tau} < 0$ and $\frac{\partial^2 K_4}{\partial\tau^2} < 0$, thus K_4 is a concave function. It is obvious that the denominator is an affine function. This completes the proof of Proposition 1.

Proposition 1 guarantees that there is a unique optimal τ^* which maximizes the EE. The complete steps of the proposed algorithm based on Dinkelbach method is summarized in Table 2.

TABLE 2. **Optimization algorithm.**

```
Algorithm Energy efficiency optimization based on Dinkelbach Method
Initialize: $\tau_{min} = 0, \tau_{max} = T, q = 0$
$k = 0$, convergence precision $\delta$;
Define: $F(\tau, q) = R_{tot}(\tau) - qE(\tau)$
While:(Convergence = False) and ($k \leq$MaxIter )do
  $\tau = \arg\ \max\{F(\tau, q)|\tau \in (\tau^*, 1)\}$
if $F(\tau, q) = 0$ then
  $\tau_0 = \tau$
  Convergence =true
 else if $F(\tau, q) \leq\delta$ then
  $\tau_\delta = \tau$
   Convergence =true
 else
   $q = \frac{R_{tot}(\tau)}{E(\tau)}$
   $k = k + 1$
 else if
 end while
```

B. OPTIMIZATION IN UNDERLAY CR-NOMA NETWORK

In this section, the EE optimization problem of underlay CR-NOMA network is presented. According to the discussion above, in underlay CR-NOMA network, since SUs will not perform spectrum sensing during the downlink subslot τ, we don't need to consider P_f, P_d, and the energy consumption of spectrum sensing P_{SS}. Thus, the optimization problem can be given as

$$\begin{aligned}&\max EE(\tau) = \frac{(1-\tau)\log_2\left(1+\sum_{i=1}^{N}\alpha_i\frac{\tau}{1-\tau}\right)}{\tau P_{CD} + (1-\tau)P_{CU}} \\ &s.t. \begin{cases}\sum_{i=1}^{N} P_i = \frac{g_i P_a \tau}{1-\tau} \\ \sum_{i=1}^{N} P_i g_s \leq I_{\max}\end{cases}\end{aligned} \tag{23}$$

According to the constraints of I_{max} and g_s, we can obtain the relationship between τ and P_i, g_s as follows:

$$\tau \leq \frac{I_{\max}}{P_a g_s g_i + I_{\max}} \tag{24}$$

Combining the results in subsection A, if we define the optimal downlink subslot as τ^* in the overlay CR-NOMA network, τ_0^* in the underlay network is expressed as

$$\tau_0^* = \min\left\{\tau^*, \frac{I_{\max}}{P_a g_s g_i + I_{\max}}\right\} \tag{25}$$

IV. SIMULATION AND DISCUSSIONS

In this section, the proposed SWIPT based CR-NOMA system model is simulated. The following simulation parameters for the Rayleigh fading channel are used. Details are presented as follows: the number of user $N = 3$, $T = 1$s, P_a is set to [1W, 2W, 5W], P_{SS} is set to [1W, 2W, 5W], $P_{CD} = 2$W, $P_{CU} = 1$W, γ_i is set to [10, 20, 30], h_i is set to [0.8, 0.7, 0.6], $\bar{P}_d = 0.7$, $\delta = 10^{-6}$, I_{max} is more than 0.5, g_s is set to [1.5, 2, 3], PH_0 is set to [0.5, 0.7, 0.9].

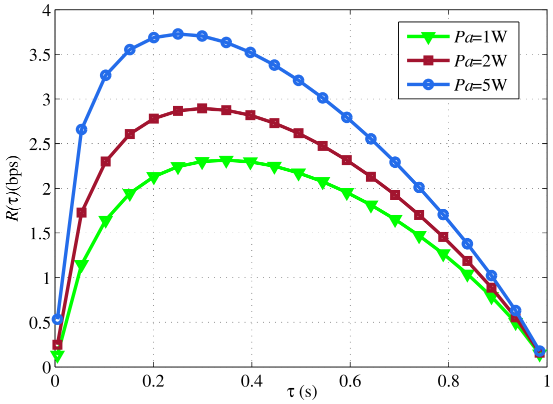

FIGURE 4. Total throughput for overlay network versus subslot τ.

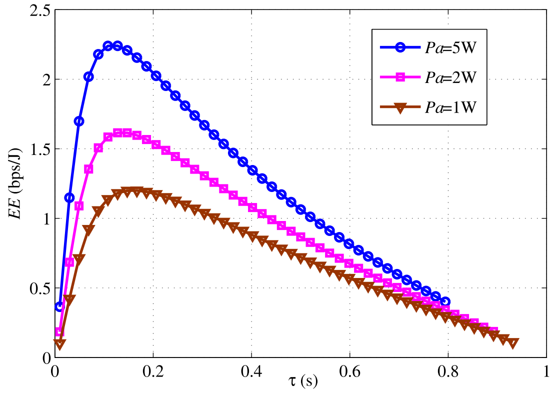

FIGURE 5. Energy efficiency for overlay network versus subslot τ.

Fig. 4 shows the sum rate of overlay CR-NOMA network versus the downlink subslot τ. As shown in Fig.4, there exists an optimal τ^* that maximizes the sum rate of overlay CR-NOMA network. In the simulation, τ^* is between 0.25 and 0.29. What's more, the sum rate increases with the increase of P_a.

Fig. 5 shows EE versus the downlink subslot τ in the overlay mode. We can conclude that there exists an optimal τ^* that maximizes EE when $\frac{\partial R_i(\tau)}{\partial \tau} < 0$. In addition, all the curves in Fig. 4 and Fig. 5 show the same trend of "first increase and then decrease". With the increase of τ, the probability of false alarm P_f decreases according to (9), and the spectrum sensing performance improves. Therefore, EE increases, i.e.,"first increase". However, the more time for the energy harvesting is, the less time for the information transmission is. Thus, the sum rate and EE decrease, i.e.,"then decrease". The optimal subslot τ^* based on the Dinkelbach method can be obtained as $\tau^* = 0.108$, and the corresponding $EE_{max} = 2.30$. We can also see that the larger P_a is, the higher EE can achieve.

Fig. 6 demonstrates the relationship between transmit power and EE for a fixed τ in the overlay mode. We can observe that EE increases with the increase of P_a. Increasing P_a indicates that the transmit power of each SU P_i during the uplink subslot also increases. Thus, the sum rate and EE of CR-NOMA increase with the increase of P_a. In Fig. 6, we can see the effect of sensing power P_{SS} on EE. For a fixed subslot τ, the sum rate is constant, the smaller the value of P_{SS} is, the smaller the energy consumption is, thus the EE increases.

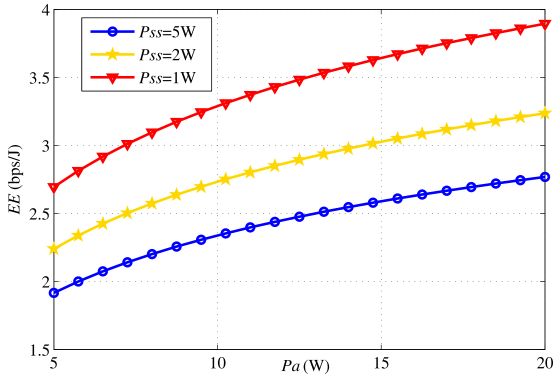

FIGURE 6. Energy efficiency versus transmission power P_a.

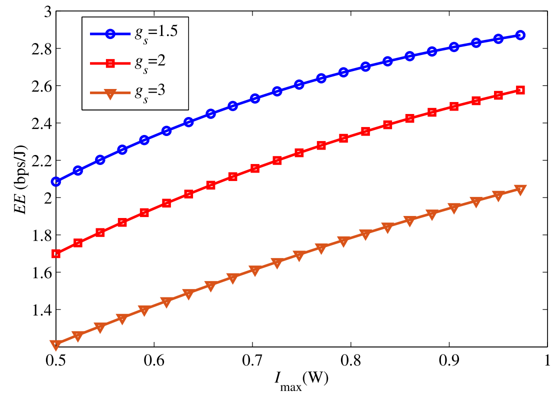

FIGURE 7. Energy efficiency versus interference threshold I_{max} of SUs.

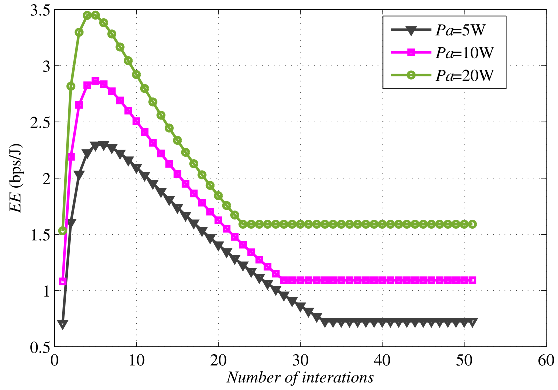

FIGURE 8. Energy efficiency versus the number of iterations.

Fig. 7 shows the relationship between EE and interference threshold I_{max} in the underlay mode. With the increase of I_{max}, SUs have a higher probability of utilizing the channel. Thus, the sum rate and EE increase. Conversely, the channel gain of PU has an opposite effect on energy efficiency. We can see that the EE decreases with the increase of g_s.

Fig. 8 shows the convergence versus the number of iterations. As mentioned above, the proposed algorithm immediately jumps out of the loop if $F(\tau, q) \leq 0$, thus we hold that the EE converges to the last value of the q array after a few iterations. This phenomenon confirms the convergence and effectiveness of the proposed algorithm. We can observe from Fig. 8 that the larger the value of P_a is, the faster the algorithm converges.

V. CONCLUSION

In this article, considering low spectrum utilization and limited battery capacity, a SWIPT based CR-NOMA system model is proposed, and the EE optimization is investigated. Wherein, two network modes are considered, i.e., overlay network and underlay network. Specifically, in the overlay mode, SUs perform spectrum sensing and SUs can transmit information only when PU is detected to be absent. In the underlay mode, SUs and PU can utilize the spectrum resource simultaneously as long as the interference is below a certain threshold. SWIPT is applied to achieve the best tradeoff between information transmission and lifetime of energy-limited networks. Specifically, SUs harvest energy during the downlink subslot while transmitting information during the uplink subslot. In addition, NOMA is used to transmit information for the secondary CR network. EE is optimized under the constraints of total transmit power, total transmission slot, interference threshold and channel gain of PU. Then, an iterative algorithm based on the Dinkelbach method is proposed to solve the optimization problems. Simulation results show that the proposed SWIPT based CR-NOMA model can achieve a tradeoff between EE and downlink subslot. Considering that NOMA is an evolution of OFDMA rather than a revolution, thus the signal on the subchannel is still an OFDM signal. The resource allocation of OFDM-NOMA system will be studied in the future work. Moreover, for the poor channel performance of direct transmission link, the resource allocation of SWIPT based CR-NOMA cooperative relay system will be studied in the future work.

REFERENCES

[1] A. Ghasemi and E. S. Sousa, "Spectrum sensing in cognitive radio networks: Requirements, challenges and design trade-offs," *IEEE Commun. Mag.*, vol. 46, no. 4, pp. 32–39, Apr. 2008. doi: 10.1109/MCOM.2008.4481338.

[2] X. Liu, M. Jia, Z. Na, W. Lu, and F. Li, "Multi-modal cooperative spectrum sensing based on dempster-shafer fusion in 5G-based cognitive radio," *IEEE Access*, vol. 6, pp. 199–208, 2018.

[3] X. Liu, X. Zhang, M. Jia, L. Fan, W. Lu, and X. Zhai, "5G-based green broadband communication system design with simultaneous wireless information and power transfer," *Phys. Commun.*, vol. 28, pp. 130–137, Jun. 2018.

[4] N. Zabetian, M. Baghani, and A. Mohammadi, "Rate optimization in NOMA cognitive radio networks," in *Proc. 8th Int. Symp. Telecommun. (IST)*, Sep. 2016, pp. 62–65. doi: 10.1109/ISTEL.2016.7881783.

[5] S. Li, S. Xiao, M. Zhang, and X. Zhang, "Power saving and improving the throughput of spectrum sharing in wideband cognitive radio networks," *J. Commun. Netw.*, vol. 17, no. 4, pp. 394–405, Aug. 2015. doi: 10.1109/JCN.2015.000070.

[6] Y.-C. Liang, Y. Zeng, E. C. Y. Peh, and A. T. Hoang, "Sensing-throughput tradeoff for cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 4, pp. 1326–1337, Apr. 2008. doi: 10.1109/TWC.2008.060869.

[7] X. Liu, M. Jia, X. Zhang, and W. Lu, "A novel multichannel Internet of Things based on dynamic spectrum sharing in 5G communication," *IEEE Internet Things J.*, vol. 6, no. 4, pp. 5962–5970, Aug. 2019. doi: 10.1109/JIOT.2018.2847731.

[8] X. Zeng, W. Li, and Y. Ma, "Directional-transmission-based solution for hidden and exposed terminal problems in inter-vehicular network," in *Proc. 3rd Int. Conf. Consum. Electron., Commun. Netw.*, Nov. 2013, pp. 289–292. doi: 10.1109/CECNet.2013.6703328.

[9] G. Liu, Y. Xu, Z. He, Y. Rao, J. Xia, and L. Fan, "Deep learning-based channel prediction for edge computing networks toward intelligent connected vehicles," *IEEE Access*, vol. 7, pp. 114487–114495, 2019.

[10] M. Al-Imari, P. Xiao, and M. A. Imran, "Receiver and resource allocation optimization for uplink NOMA in 5G wireless networks," in *Proc. Int. Symp. Wireless Commun. Syst. (ISWCS)*, Aug. 2015, pp. 151–155. doi: 10.1109/ISWCS.2015.7454317.

[11] Y. Saito, A. Benjebbour, Y. Kishiyama, and T. Nakamura, "System-level performance evaluation of downlink non-orthogonal multiple access (NOMA)," in *Proc. IEEE 24th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2013, pp. 611–615. doi: 10.1109/PIMRC.2013.6666209.

[12] H. Zuo and X. Tao, "Power allocation optimization for uplink non-orthogonal multiple access systems," in *Proc. 9th Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2017, pp. 1–5. doi: 10.1109/WCSP.2017.8171176.

[13] Z. Na, J. Lv, F. Jiang, M. Xiong, and N. Zhao, "Joint subcarrier and subsymbol allocation-based simultaneous wireless information and power transfer for multiuser GFDM in IoT," *IEEE Internet Things J.*, vol. 6, no. 4, pp. 5999–6006, Aug. 2019.

[14] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, "Non-orthogonal multiple access (NOMA) for cellular future radio access," in *Proc. IEEE 77th Veh. Technol. Conf. (VTC Spring)*, Jun. 2013, pp. 1–5. doi: 10.1109/VTCSpring.2013.6692652.

[15] Z. Song, X. Wang, Y. Liu, and Z. Zhang, "Joint spectrum resource allocation in noma-based cognitive radio network with SWIPT," *IEEE Access*, vol. 7, pp. 89594–89603, 2019. doi: 10.1109/ACCESS.2019.2926429.

[16] T. A. Zewde and M. C. Gursoy, "NOMA-based energy-efficient wireless powered communications in 5G systems," in *Proc. IEEE 86th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2017, pp. 1–5. doi: 10.1109/VTC-Fall.2017.8288114.

[17] "5G radio access: Requirements, concepts and technologies," NTT DOCOMO, Inc., White Paper, Jul. 2014. [Online]. Available: https://www.nttdocomo.co.jp/english/binary/pdtJcorporate/technology/whitepaper-5g/DOCOMO-5G-White]aper.pdf

[18] F. Zhu, F. Gao, and M. Yao, "A new cognitive radio strategy for SWIPT system," in *Proc. Int. Workshop High Mobility Wireless Commun.*, Nov. 2014, pp. 73–77. doi: 10.1109/HMWC.2014.7000217.

[19] H. Bao, C. Zhang, L. Wu, and M. Li, "Design of physical layer secure transmission scheme based on SWIPT NOMA systems," in *Proc. IEEE 17th Int. Conf. Commun. Technol. (ICCT)*, Oct. 2017, pp. 6–9. doi: 10.1109/ICCT.2017.8359473.

[20] Z. Na, Y. Wang, X. Li, J. Xia, X. Liu, M. Xiong, and W. Lu, "Subcarrier allocation based simultaneous wireless information and power transfer algorithm in 5G cooperative OFDM communication systems," *Phys. Commun.*, vol. 29, pp. 164–170, Aug. 2018.

[21] Z. Song, X. Wang, Y. Liu, and Z. Zhang, "Joint spectrum resource allocation in NOMA-based cognitive radio network with SWIPT," *IEEE Access*, vol. 7, pp. 89594–89603, 2019.

[22] W. Lu, Y. Gong, J. Wu, H. Peng, and J. Hua, "Simultaneous wireless information and power transfer based on joint subcarrier and power allocation in OFDM systems," *IEEE Access*, vol. 5, pp. 2763–2770, 2017. doi: 10.1109/ACCESS.2017.2671903.

[23] Z. Na, J. Lv, M. Zhang, B. Peng, M. Xiong, and M. Guan, "GFDM based wireless powered communication for cooperative relay system," *IEEE Access*, vol. 7, pp. 50971–50979, 2019.

[24] M. Shaat and F. Bader, "Joint resource optimization in decode and forward multi-relay cognitive network with direct link," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2012, pp. 1398–1403. doi: 10.1109/WCNC.2012.6213999.

[25] J. Mao, G. Xie, J. Gao, and Y. Liu, "Energy efficiency optimization for OFDM-based cognitive radio systems: A water-filling factor aided search method," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2366–2375, May 2013. doi: 10.1109/TWC.2013.013013.121013.

[26] H. Zhang, S. Huang, C. Jiang, K. Long, V. C. W. Leung, and H. V. Poor, "Energy efficient user association and power allocation in millimeter-wave-based ultra dense networks with energy harvesting base stations," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 9, pp. 1936–1947, Sep. 2017. doi: 10.1109/JSAC.2017.2720898.

[27] S. Li, L. Guo, P. Zhang, H. Wang, Z. Cai, X. Zhu, Y. Feng, and C. Zhang, "Modeling and optimization on energy efficiency of urban integrated energy system," in *Proc. 2nd IEEE Conf. Energy Internet Energy Syst. Integr. (EI)*, Oct. 2018, pp. 1–6.

[28] Y. Sun, Y. Zha, and L. Chen, "Robust energy efficiency optimization for coordinated transmission with transceiver impairments in private TD-LTE wireless network," in *Proc. China Int. Conf. Electr. Distrib. (CICED)*, Sep. 2018, pp. 1454–1457.

[29] H. Hu, H. Zhang, and Y.-C. Liang, "On the spectrum- and energy-efficiency tradeoff in cognitive radio networks," *IEEE Trans. Commun.*, vol. 64, no. 2, pp. 490–501, Feb. 2016. doi: 10.1109/TCOMM.2015.2505281.

[30] Q. Sun, L. Li, and J. Mao, "Simultaneous information and power transfer scheme for energy efficient MIMO systems," *IEEE Commun. Lett.*, vol. 18, no. 4, pp. 600–603, Apr. 2014. doi: 10.1109/LCOMM.2014.022514.132763.

[31] F. Zhou, Z. Li, N. C. Beaulieuz, J. Cheng, and Y. Wang, "Resource allocation in wideband cognitive radio with SWIPT: Max-min fairness guarantees," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–6.

[32] K. Lee and J.-P. Hong, "Energy-efficient resource allocation for simultaneous information and energy transfer with imperfect channel estimation," *IEEE Trans. Veh. Technol.*, vol. 65, no. 4, pp. 2775–2780, Apr. 2016. doi: 10.1109/TVT.2015.2416754.

[33] C. Zhang, H. Zhao, W. Li, K. Zheng, and J. Yang, "Energy efficiency optimization of simultaneous wireless information and power transfer system with power splitting receiver," in *Proc. IEEE 25th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2014, pp. 2135–2139. doi: 10.1109/PIMRC.2014.7136525.

[34] W. Dinkelbach, "On nonlinear fractional programming," *Manage. Sci.*, vol. 13, no. 7, pp. 492–498, 1967. doi: 10.1287/mnsc.13.7.492.

[35] D. Jiang, H. Zheng, D. Tang, and Y. Tang, "Relay selection and power allocation for cognitive energy harvesting two-way relaying networks," in *Proc. IEEE 5th Int. Conf. Electron. Inf. Emergency Commun.*, May 2015, pp. 163–166. doi: 10.1109/ICEIEC.2015.7284511.

[36] Y. Zhang, Q. Yang, T.-X. Zheng, H.-M. Wang, Y. Ju, and Y. Meng, "Energy efficiency optimization in cognitive radio inspired non-orthogonal multiple access," in *Proc. IEEE 27th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2016, pp. 1–6.

[37] D. Wang and S. Men, "Secure energy efficiency for NOMA based cognitive radio networks with nonlinear energy harvesting," *IEEE Access*, vol. 6, pp. 62707–62716, 2018. doi: 10.1109/ACCESS.2018.2876970.

[38] F. Zhou, Y. Wu, R. Q. Hu, Y. Wang, and K. K. Wong, "Energy-efficient NOMA enabled heterogeneous cloud radio access networks," *IEEE Netw.*, vol. 32, no. 2, pp. 152–160, Mar. 2018.

[39] W. Zhao, R. She, and H. Bao, "Energy efficiency maximization for two-way relay assisted CR-NOMA system based on SWIPT," *IEEE Access*, vol. 7, pp. 72062–72071, 2019.

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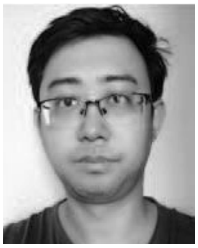

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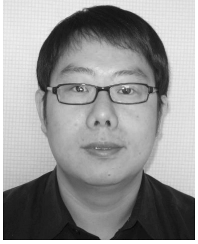

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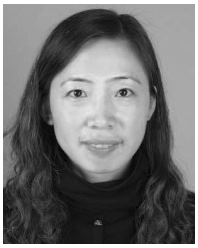

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