Improvement of the Sum Rate and Energy Efficiency of IA-based Cognitive Radio Network by Successive Relaying and Power Allocation

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***Abstract*-- In this paper, we propose an underlay cognitive radio network that consists of several secondary users and one successive relaying-aided primary user. Two half-duplex relays operate as full-duplex relays in the successive relaying technique. To improve spectral efficiency, the primary user utilizes the successive relaying technique. Inter relay interference and inter-user interference are challenges of the proposed network. For eliminating these interferences, the interference alignment method is utilized. Also, two power allocation algorithms are proposed to maximize the sum rate of secondary users and the energy efficiency of the network. In both power allocation algorithms, satisfying the quality of service of the primary user is considered. The closed-form solutions of these algorithms are obtained. We use the fractional programming approach to solve energy efficiency optimization in two steps.**

***Index Terms*-- Cognitive radio network, Interference suppression, Interference alignment, Power allocation, Successive relay, Inter relay interference.**

I. INTRODUCTION

These days, the number of devices connected to the wireless network has increased, among other reasons, because of some technologies such as the internet of things and device-to-device communications. Therefore, operators have to improve coverage, network capacity, reliability, and spectrum management while reducing operating costs. Thus, new approaches, for example, spectral sharing, full-duplex relays, and their combination, help improve coverage, energy efficiency, and spectral efficiency [1, 2].

Spectrum sharing in cognitive radio networks (CRN) is an approach to overcome spectral resource deficiency [3, 4]. CRN consists of primary users (PUs) and secondary users (SUs). SUs are allowed to use the spectrum of PUs to send their data while guaranteeing the performance of the PUs [5]. PUs share their spectrum in two ways: Overlay spectrum sharing and Underlay spectrum sharing. In the Overlay spectrum sharing, SUs can use the spectrum without PUs. In the Underlay spectrum sharing, SUs can simultaneously use the spectrum with PUs. Thus, interferences appear in all receivers. In this situation, the transmitted power of SUs should be controlled because of decreasing the interference in PU’s receiver and guaranteeing their performance [6, 7]. Thus, improving the rate of secondary users by considering the quality of service (QoS) of PUs is one of the spectrum sharing challenges [8].

The CRN is an interference network so, cancellation of all interference is necessary. Interference alignment (IA) is one of the interference cancellation methods that has attracted enormous interest recently. The best definition of IA is aligning all interference in one subspace to increase free interference dimensions for the desired signal [9, 10]. IA provides a convenient transmission without any interference. The received SINR of PU is decreased compared to the situation without SUs and IA technique so, the QoS of PU is decreased [11]. Therefore using the relays in CRN is one of the powerful ways to improve CRN performance [12, 13]. Furthermore, power allocation is another effective approach to cope with this challenge [38].

In addition to the CRN, cooperative networks (relays) have also presented to overcome challenges such as the shortage of spectrum resources, higher QoS demands for users, and lower power consumption for transmission. A cooperative network in telecommunication systems increases network coverage and counteracts the effect of path loss. With a given power consumption, relay networks achieve higher capacity than networks without relays. [14, 15]. Therefore, relays help to save power. This feature improves the energy efficiency of the network. Accordingly, in a cognitive radio network, relays help to save more power to serve SUs [16-19]. Relays are divided into two groups, namely full-duplex and half-duplex relays. Two time-frequency resources are required in the end-to-end transmission between the source and destination with the help of half-duplex (HD) relays [20]. But in full-duplex (FD) relays transmission, one time-frequency resource is required. In other words, FD relays send and receive simultaneously in the same bandwidth. Accordingly, the required resources (bandwidth and time) are reduced to half also spectral efficiency is increased compared to HD relays. The main challenge of the FD relays is the interference from the transmitter side of the relay to the own receiver, which is known as self-interference (SI). Much research has been done to eliminate this interference, but it is not eliminated in practice [21, 22]. The receiver and transmitter of the relay are in the same device. As a result, self-interference from receiver to own receiver is strong. Hence, management and cancellation of self-interference are complex [22].

Authors in [23] proposed a successive relaying (SR) scheme that performs as the full-duplex relay. SR scheme consists of a source, a destination, and two relays in each

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time slot, one of them is in transmit mode, and the other one is in receive mode. The receiver relay receives a new data frame from the source while the other forwards the previous data frame to the destination. Then, in the next time slot, relays change their mode. All the transmissions are simultaneously and have the same bandwidth; therefore, the receiver relay receives interference from the transmitter relay. This interference is called inter relay interference (IRI) [24].

In successive relay performance, the distance between the relays is more than the distance between transmitter and receiver of the FD relay, so IRI is weaker than SI. If the relays are far apart, the intensity of the IRI is very low and can be ignored. Furthermore, if relays are close to each other, IRI is strong; hence it can be decoded entirely and removed from the received signal in the receiver relay [25]. Besides, according to the complexity and cost of implementing SI cancellation in FD relays [24] and utilizing the present devices, SR can be effective, and thus some researchers are interested [26-29]. Therefore, the SR technique and power allocation in CRN are effective. In the following subsection, we express some research in this field.

Related Works:

The combination of SR and CRN (cooperative CRN) creates different system models that improve spectral efficiency and decrease the transmitted power. Additionally, an appropriate power allocation enhances the performance of this network [30-33]. In [30], spectrum sharing is done with the help of SR. Then, the transmission rate is maximized. In this paper, there are two Sus and one PU, where transmitters of the SUs operate as relays for PU in the SR technique. Authors in [31] proposed a network that the two relays of the SR method act as SU transceivers while serving as relays for PU. This paper uses the IRI between the two relays to transmit the SU data. Then, two optimization problems are formulated to minimize the BER and maximize the average achievable rate. Also, [32] proposed a hybrid satellite system with the help of the SR technique and then maximized the system's capacity. In [33], there are two secondary and one primary network. The secondary networks consist of a base station and many users. Base stations of secondary networks act as the relays for PU by SR. Then, by maximizing the rate of secondary networks, design the beamforming matrix.

Our Works:

In this paper, we propose an underlay spectrum sharing CRN that utilizes the SR technique in the PU to improve the QoS of PU while increasing the rate of SUs. Utilizing the SR technique in PU to save more power for SUs has not been proposed previously. Besides, we apply the power allocation technique to optimize the network's performance. In the SR technique, we need to manage the IRI. Some analyses of IRI partial or full cancellation [34, 35]. This paper applies IA to eliminate all interferences in CRN and IRI. One of our new works in this paper is adopting the IA method to manage IRI. Spectral efficiency and energy efficiency (EE) are significant parameters in green communication [36]. Therefore, the main goal of this paper is spectral and energy efficiency optimization of the network with considering QoS of PU. Our investigations for spectral efficiency and energy efficiency are as follows:

- In CRN, the quality of service of PU should be guaranteed. Therefore, we first obtain the minimum transmitted power to satisfy the QoS of PU. We apply an appropriate approximation in our equations for Simplification.
- Next, we propose a power allocation for maximizing the sum rate of SUs while guaranteeing the QoS of the PU. Then, we obtain the closed-form solution for the problem.
- Also, we propose a power allocation problem to maximize the energy efficiency of the network. Because of the complexity of the problem, we solve it in two steps. Therefore, the final solution is expressed as an algorithm. In this algorithm, the QoS of PU is considered.

The proposed optimization problems in this work have not been solved previously. Because of the appropriate approximation, the closed-form results are easily obtained.

This paper is organized as follows: In Section 2, the proposed system model, the SR scheme, the cognitive radio network, and the IA method are described. In Section 3, two power allocation algorithms optimize the network's sum rate of Sus and EE. Then in Section 4, the results are simulated, and section 5 is the paper's conclusion.

Notation: $\mathbf{I}_d$ represents the $d \times d$ identity matrix. $\mathbf{A}^\dagger$ and $|\mathbf{A}|$ are the Hermitian transpose and the determinant of matrix A, respectively. $\|a\|$ is the ℓ2-norm of vector a. |a| is the absolute value of complex number a. $\mathbb{C}^{M \times N}$ is the space of complex M × N matrices. $\mathcal{CN}$(a, **A**) is the complex Gaussian distribution with mean a and covariance matrix A.

II. SYSTEM MODEL

As shown in Fig. 1, the proposed system model in this paper is a cognitive radio network including *K* users. One of them is a PU, and *K-1* of them are SUs. PU consists of one source, one destination, and two half-duplex amplify and forward (AF) relays that act as SR techniques. Each SU consists of one transmitter and one receiver. They use the PU spectrum for transmission. Therefore, we have an interference network (IRI and inter-users interference). We apply the IA technique to eliminate interferences of this network. Therefore, we have to consider that all nodes are multi-antennas.

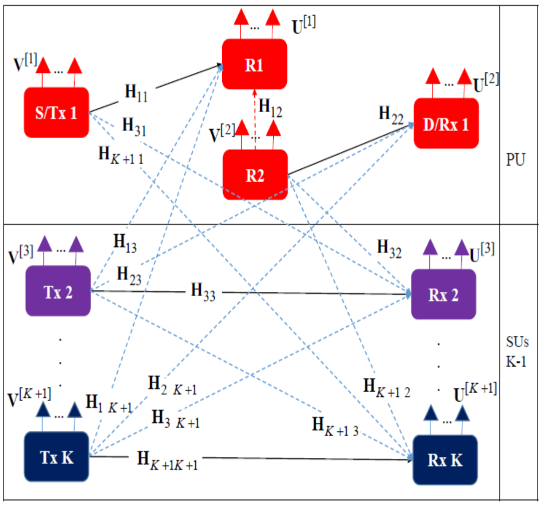

Fig. 1. IA-based CRN Model with 1 SR PU and K-1 SUs in Odd TS

In this section, we will describe the performance of the SR technique and the IA-based CRN model with SR PU. Then, the QoS requirement of the PU will be analyzed.

A. Successive Relaying Technique

As shown in Fig. 1, PU utilizes the SR technique. Relays in PU are shown as R1 and R2 in the figure. The SR performance for different time slots is as follows.

Here, the primary user sends *L* (*L* is even) messages from the source to the destination.

First Time Slot:

The source sends the first message to the R1 (relay in receive mode). R2 doesn't have any message to send in this time slot, so it's off.

Second-time Slot (Even Time Slots):

R2 is in receive mode during this time slot, and R1 is in transmit mode. Source and R1 send their massages simultaneously. Source sends a new message (second massage) to R2. Then, R1 amplifies the received message in the previous time slot (first massage) and then sends it to the destination. All transmissions are carried out at the same frequency. Thus, R2 receives interference from the R1. This Interference is known as inter relay interference (IRI).

Third Time Slot (Odd Time Slots):

R1 is in receive mode during this time slot, and R2 is in transmit mode. Source sends a new message (third massage) to the R1. R2 amplifies the received message in the previous time slot (second massage) and then transmits it to the destination. Thus, R1 receives interference from the R2 (red dotted line in Fig. 1).

This process continues until the *L*+1th time slot.

***L*+1th Time Slot (Last Time Slot):**

During this time slot, R2 sends the last message (the message received by R2 in the *L*th time slot) to the destination, but the source doesn't have any message to send.

According to this description, *L* messages are sent in *L* + 1time slots. This scheme act as a full-duplex relay for a large number of *L*. Thus spectral efficiency is recovered compared to HD relays. In this paper, the first and the last time slots aren't considered, and the focus is on the even and odd time slot.

B. The Proposed Cognitive Radio Network

Cognitive radio is a network that PU shares its spectrum with the Sus. Hence, all the transmissions are at the same time and frequency. Thus, we have an interference network, especially when the PU utilizes the SR technique. Here, we use some antennas in all nodes to manage the interference. Accordingly, we propose a new cognitive radio network as below:

There are *K* users (one primary user and *K-1* secondary user), and all nodes are multi-antennas. All transmitters have *N* antennas, and receivers have *M* antennas. The relays have *M* antennas in receive mode, and they use *N* of *M* antennas when they're in transmit mode. We don't consider antenna selection in this paper.

Here, the channel coefficients are uncorrelated quasi-static flat fading [37]. The proposed network is expressed only in a one-time slot (odd time slot) due to the statistical similarity of the channel coefficients.

As shown in Fig. 1, $\mathbf{H}_{11} \in \mathbb{C}^{N \times M}$ and $\mathbf{H}_{22} \in \mathbb{C}^{N \times M}$ denote source-R1 and R1-destination channel coefficients. Further, $\mathbf{H}_{k+1\ k+1} \in \mathbb{C}^{N \times M}$ determines the channel coefficient from *K*+1th SU's transmitter to its receiver ($k \in \{2,...,K\}$). The interference channel coefficients of this network are shown in Table 1:

TABLE I

INTERFERENCE CHANNELS

Channel Coefficients	Channels
$\mathbf{H}_{21} \in \mathbb{C}^{N \times M}$	Channel between R1 and R2
$\mathbf{H}_{1\ k+1} \in \mathbb{C}^{N \times M}$	The channel between *k*th SU's transmitter and R1
$\mathbf{H}_{k+1\ 2} \in \mathbb{C}^{N \times M}$	Channel between R2 and *k*th SU's receiver
$\mathbf{H}_{2\ k+1} \in \mathbb{C}^{N \times M}$	The channel between *k*th SU's transmitter and PU's destination
$\mathbf{H}_{k+1\ j+1} \in \mathbb{C}^{N \times M}$	Channel between *j*th transmitter and kth Receiver of SUs

Where $k \neq j \in \{2,...,K\}$. Each of the coefficients entities is independent and identically distributed (i.i.d.), following $\mathcal{CN}$ (0, 1).

In this paper, the channel state information is entirely known in all nodes. Therefore, the linear IA technique eliminates all interferences (CRN and IRI).

In the *n*-1th time slot, the received signal at the Relay (R2), including *d* data streams, and the received signal at the PU's destination can be expressed as (1) and (2), respectively.

$$
\begin{aligned}
&\mathbf{y}_R(n-1) = \\
&\quad \sqrt{p_t^{[S]}}\mathbf{U}^{\dagger[1]}(n-1)\mathbf{H}_{11}(n-1)\mathbf{V}^{[1]}(n-1)\mathbf{x}_S(n-1) \\
&\qquad + \sqrt{p_t^{[R]}}\mathbf{U}^{\dagger[1]}(n-1)\mathbf{H}_{21}(n-1)\mathbf{V}^{[2]}\mathbf{x}_R(n-1) + \\
&\qquad \sum_{k=2}^{K}\sqrt{p_t^{[k]}}\mathbf{U}^{\dagger[1]}(n-1)\mathbf{H}_{k+1\ 1}\mathbf{V}^{[k+1]}(n-1)\mathbf{x}_k(n-1) \\
&\qquad\quad + \mathbf{U}^{\dagger[1]}(n-1)\mathbf{z}_R(n-1)
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
\mathbf{y}_D(n) = {} & \sqrt{p_t^{[R]}}\mathbf{U}^{\dagger[2]}(n)\mathbf{H}_{22}(n)\mathbf{V}^{[2]}(n)\mathbf{x}_R(n) + \\
& \sum_{k=2}^{K}\sqrt{p_t^{[k]}}\mathbf{U}^{\dagger[2]}(n)\mathbf{H}_{k+1\ 2}(n)\mathbf{V}^{[k+1]}(n)\mathbf{x}_k(n) \\
& + \mathbf{U}^{[2]}(n)\mathbf{z}_D(n)
\end{aligned} \tag{2}
$$

Where $\mathbf{x}_R(n)$ is the amplified form of the received signal at the relay (R2) in the previous time slot ($\mathbf{x}_R(n) = \beta\mathbf{y}_R(n-1)$). In time slot *n*, the received signal at the *k*th SU's receiver can be denoted as:

$$
\begin{aligned}
\mathbf{y}_k(n) = {} & \sqrt{p_t^{[k]}}\mathbf{U}^{\dagger[k+1]}(n)\mathbf{H}_{k+1\ k+1}\mathbf{V}^{[k+1]}(n)\mathbf{x}_k(n) \\
& + \sqrt{p_t^{[R]}}\mathbf{U}^{\dagger[k+1]}(n)\mathbf{H}_{k+1\ 1}\mathbf{V}^{[2]}(n)\mathbf{x}_R \\
& + \sum_{\substack{j=2 \\ j \neq k}}^{K}\sqrt{p_t^{[k]}}\mathbf{U}^{\dagger[k+1]}(n)\mathbf{H}_{k+1\ j+1}\mathbf{V}^{[j+1]}(n)\mathbf{x}_j \\
& + \mathbf{U}^{\dagger[k+1]}(n)\mathbf{z}_k(n); k = 2,...,K
\end{aligned} \tag{3}
$$

Where, $\mathbf{U}^{[r]}, \mathbf{V}^{[r]}, r \in \{1, ..., K+1\}$ are the unitary $M \times d$ interference suppression matrix in receivers and $N \times d$ precoding matrix in transmitters, respectively.

$\mathbf{x}_a, a \in \{k \in \{2, ..., K\}, S, R\}$ includes d data streams of the SU's transmitter, the relay, and source of PU with the power of $\mathrm{E}\left[\|\mathbf{x}_a\|^2\right] = p_t^{[a]}$. $\mathbf{z}_b \in \mathbb{C}^{N\times 1}, b \in \{k \in \{2, ..., K\}, d, R\}$ is an additive white Gaussian noise (AWGN) vector with distribution $\mathcal{CN}(0, \sigma^2 \mathbf{I}_N)$ at the *k*th receiver, where σ^2 is the noise power at each antenna receiver's antenna.

When channel state information is available in all nodes, the interferences (inter-users interference and IRI) can be eliminated if the following conditions are met:

$$\mathrm{Rank}[\mathbf{U}^{\dagger[r]} \mathbf{H}_{r\,r} \mathbf{V}^{[r]}] = d; r = 1, ..., K+1 \tag{4}$$

$$\mathbf{U}^{\dagger[r]} \mathbf{H}_{r\,t} \mathbf{V}^{[t]} = 0 \ ; \forall r \neq t \ ; \ t, r = 1, ..., K+1 \tag{5}$$

Therefore, desired signals are received among the full rank channel $\mathbf{U}^{\dagger[r]} \mathbf{H}_{r\,r} \mathbf{V}^{[r]} = \bar{\mathbf{H}}_r \in \mathbb{C}^{d\times d}$. Also, we assume that the minimizing interference leakage (MinIL) Algorithm (39) is adopted to calculate the solutions of IA. Hence the received signals in (1), (2), and (3) can be rewritten as:

$$\mathbf{y}_R(n-1) = \sqrt{p_t^{[s]}} \bar{\mathbf{H}}_1 \mathbf{x}_S + \bar{\mathbf{z}}_R \tag{6}$$

$$\mathbf{y}_D(n) = \sqrt{p_t^{[R]}} \bar{\mathbf{H}}_2 \mathbf{x}_R + \bar{\mathbf{z}}_D \tag{7}$$

$$\mathbf{y}_k(n) = \sqrt{p_t^{[k]}} \bar{\mathbf{H}}_{k+1} \mathbf{x}_k + \bar{\mathbf{z}}_k(n); k = 2, ..., K \tag{8}$$

Where $\bar{\mathbf{z}}_a = \mathbf{U}^{[r]} \mathbf{z}_a$ is AWGN with CN $(0, \sigma^2 \mathbf{I}_d)$ distribution.

Since this paper mainly concentrates on power allocation and doesn't consider the degrees of freedom, the transmitter sends one data stream (d = 1). Hence, the number of users can be present in this network should follow:

$$K < M + N - 2 \tag{9}$$

When conditions (4) and (5) are met, the IA technique eliminates interferences. Due to *d* = 1, the signals are received among the full rank channel $h_r = \mathbf{u}^{\dagger[r]} \mathbf{H}_{r\,r} \mathbf{v}^{[r]} = \bar{\mathbf{H}}_r \in \mathbb{C}^{1\times 1}$. Consequently, the amplifying factor at the relay and the signal to noise ratio (SNR) of the PU and SUs can be obtained as (10), (11), and (12), respectively:

$$\beta = \frac{1}{\sqrt{|y_R(n-1)|^2}} = \frac{1}{\sqrt{p_t^{[S]} |h_1|^2 + \sigma^2}} \tag{10}$$

$$SNR^{[1]} = \frac{p_t^{[R]} p_t^{[S]} |h_2|^2 |h_1|^2 \ d_{RD}^{-\alpha} d_{SR}^{-\alpha}}{p_t^{[R]} |h_2|^2 \ d_{RD}^{-\alpha} \sigma^2 + p_t^{[S]} |h_1|^2 \ d_{SR}^{-\alpha} \sigma^2 + \sigma^4} \tag{11}$$

$$SNR^{[k]} = \frac{|h_{k+1}|^2 \ d_k^{-\alpha} P_t^{[k]}}{\sigma^2}, k = 2, ..., K \tag{12}$$

Where d_{RD}, d_{SR} are the distances between relay-destination and source-relay, respectively. d_k is the distance between the transmitter and receiver of the *k*th user and α is the channel attenuation factor. $h_r = \mathbf{u}^{\dagger[r]} \mathbf{H}_{r\,r} \mathbf{v}^{[r]}$ where $\mathbf{H}_{r\,r}$ is i.i.d with $\mathcal{CN}$ (0, 1) distribution. $\mathbf{u}$, $\mathbf{v}$ are the unitary vectors that they're independent of $\mathbf{H}_{r\,r}$. Therefore, h_r is i.i.d with $\mathcal{CN}$(0, 1) distribution, too [38, Appendix E].

C. *Primary User's Quality of Service*

In an underlay spectrum sharing CR network, SUs cannot be present unless the interferences from SUs don't decrease the PU's performance. Consequently, the power of noise and interference in the primary user must be low. If IA is applied, interferences can all be eliminated. Therefore, IA can provide a convenient spectrum sharing, which the interference need not be considered any longer. But, the SINR of PU is reduced compared to MIMO PU without IA and SUs [11], and it doesn't guarantee the QoS of PU. A threshold rate for the PU () is defined to satisfy QoS to tackle this challenge. Accordingly, the minimum required transmitted power of the PU should follow:

$$R_{th}^{[1]} < \log_2\left(1 + SNR^{[1]}\right) \tag{13}$$

In the IA-based CR network, the SUs should try to satisfy the QoS requirement of the PU defined in (13) unless they will not be allowed to access the licensed spectrum.

III. POWER ALLOCATION ALGORITHMS IN THE COGNITIVE RADIO NETWORK

In most previous works in this field, equal transmitted power is allocated to each user. However, this may not be an appropriate power allocation. In this section, an optimum power allocation among users is applied, under the condition that the sum transmitted power of the users should be lower than $p_{\max}$.

Here, the minimum transmitted power of the PU (power of the source and the relay) to guarantee the threshold rate is first presented. Then two power allocation algorithms are proposed.

A. *Minimal Power of PU to Guarantee its QoS Requirement*

In the proposed network, when the PA among users is considered, the threshold rate of the PU should be satisfied. In this section, the minimum required transmitted power of the relay and the source are obtained to ensure the PU's QoS. We assume the power of the source and relay are equal ($p_t^{[S]} = p_t^{[R]} = p_t^{[1]}$). Then, the minimum required power for the relay and source are obtained as (14) while solving (13).

$$\begin{aligned} & p_t^{[S]} = p_t^{[R]} = p_t^{[1]} \geq \\ & p_{t\_\min} = \sigma^2 \frac{((2^{R_{th}^{[1]}} - 1)(|h_2|^2 d_{RD}^{-\alpha} + |h_1|^2 d_{SR}^{-\alpha})) + \sqrt{(2^{R_{th}^{[1]}} - 1)^2 (|h_2|^2 d_{RD}^{-\alpha} + |h_1|^2 d_{SR}^{-\alpha})^2 + 4(2^{R_{th}^{[1]}} - 1)|h_2|^2 |h_1|^2 d_{RD}^{-\alpha} d_{SR}^{-\alpha}}}{2|h_2|^2 |h_1|^2 d_{RD}^{-\alpha} d_{SR}^{-\alpha}} \end{aligned} \tag{14}$$

In this paper, the power allocation algorithms mainly depend on two constraints. The first constraint is the maximum sum of transmitted powers. The second one is the minimal required transmitted power of the relay and the source. According to these constraints, two cases are introduced to assign the power to the PU and SUs. Thus $p_t^{[1]}$ follows (15).

$$\begin{cases} p_t^{[1]} = p_{\max}/2 & ;If \ \ 2p_{t\_\min} > p_{\max} \\ p_{t\_\min} \le p_t^{[1]} \le p_{\max}/2 & ;If \ \ 2p_{t\_\min} \le p_{\max} \end{cases} \tag{15}$$

According to (15), the cases are explained as follows:

$2p_{t\_\min} > p_{\max}$: It means the PU's power requirement cannot be satisfied. Therefore, the maximum power ($p_{\max}$) is allocated to the PU's relay and source to increase the rate. In this case, SUs cannot use the PU's spectrum, and they're off.

$2p_{t\_\min} \le p_{\max}$: It means the minimum required transmitted power of the source, relay, and then $R_{th}^{[1]}$ can be satisfied. Therefore, according to the power allocation, the transmitted power of the source and the transmitted power of the relay is in $\left[p_{t\_\min}, {}^{p_{\max}}\!/_{2} \right]$ range. In this case, PU and probably SUs are active. The SUs should be off if there is no power to allocate them ($2p_{t\_\min} = p_{\max}$).

Algorithm 1 (SRPA)

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$p_{t\_\min}$ is calculated according to (14).
if $2p_{t\_\min} < p_{\max}$, then
    $p_t^{[1]} = p_{t\_\min}$.
    $p_{\max} - 2p_{t\_\min}$ is allocated to SUs by (17) and (18)
else
    Allocate $p_{\max}$ to the PU.
    SUs are switched into sleep mode.
end if
Transmission for duration T with the power allocated.
The time slot ends.
```

B. Power Allocation Algorithm for Maximizing SU's Sum Rate

In the spectrum trading-based CRN, the income of PUs is proportional to the sum rate of SUs they provided. Besides, when multiple PUs sell spectrum to multiple SUs, SUs can adapt their behavior by observing the variations in price and quality of spectrum offered by these PUs [38]. In this section, the sum rate of the SUs is maximized while considering the PU's $R_{th}^{[1]}$ constraint. As a result, a power allocation algorithm is proposed as follows:

If $2p_{t-\min} \le p_{\max}$ the required transmitted power of the source and the relay ($p_{t\_\min}$) is assigned to them. Next, the residual power is allocated to SUs to maximize their sum rate or spectral efficiency. The power allocation problem is denoted as:

$$\begin{cases} \max\limits_{P_t^{[2]},P_t^{[3]},\dots,P_t^{[k]}} \ \sum\limits_{k=2}^{K} \log_2\left(1 + d_k^{-\alpha} \left| h_{k+1} \right|^2 \dfrac{p_t^{[k]}}{\sigma^2} \right) \\ \quad s.t. \quad p_t^{[k]} \ge 0, \forall k = 2,\dots,K \\ \qquad\qquad \sum\limits_{2}^{K} p_t^{[k]} = p_{\max} - 2p_{t\_\min} \end{cases} \tag{16}$$

which is similar to the PA problem in multiple parallel channels. Therefore, the water-filling PA method is exploited, and the closed-form solution for the optimal transmitted power of the SUs is obtained as (17).

$$p_t^{*[k]} = (\upsilon - \frac{\sigma^2}{d_k^{-\alpha} \, | h_{k+1} |^2})^+ \tag{17}$$

Where, $x^+ = \max(x,0)$ and υ should satisfy (18).

$$\sum_{k=2}^{K} (\upsilon - \frac{\sigma^2}{d_k^{-\alpha} \, | h_{k+1} |^2})^+ = p_{\max} - 2p_{t\_\min} \tag{18}$$

The closed-form solution of (15) that is expressed as (17) and (18) is easy to obtain. Hence, the computational complexity of the proposed algorithm (Algorithm 1) is reduced.

C. Power Allocation Algorithm for Maximizing EE of Network

In the future, since the number of devices is increased, energy management is critical to prevent economic and environmental problems. Power allocation is one of the effective ways to increase EE. The EE of the network can be defined as the transmitted information per unit frequency per Joule energy consumption (bits/Hz/Joule).

This section studies the EE of the CRN using the SR PU. Here, we want to show that the EE of the proposed network is increased, although relays add extra circuit power in each time slot. We propose a power allocation problem to maximize the EE. The problem is denoted as (19).

Where p_{ct}, p_{cr} is the circuit power of the transmitters and the receivers (the source and the relay in transmit mode is also included).

Problem (19) is complex because it's concave-convex fractional programming [40]. When $2p_{t-\min} \le p_{\max}$ (19) has an optimal solution. Part 1 and part 2 are first provided to obtain the closed-form solution of (19).

$$\max_{p_t^{[1]},\dots,p_t^{[K]}} \ EE = \max \frac{\log_2(1+SNR^{[k]}) + \sum\limits_{k=2}^{K} \log_2(1+p_t^{[k]} \dfrac{d_k^{-\alpha} \, | h_{k+1} |^2}{\sigma^2})}{\left(K+1\right)\left(p_{ct}+p_{cr}\right) + 2p_t^{[1]} + \sum\limits_{k=2}^{K} p_t^{[k]}}$$
$$p_t^{[k]} \ge 0, p_t^{[1]} \ge p_{t\_\min}, k = 2,\dots,K$$
$$2 \times p_t^{[1]} + \sum_{k=2}^{K} p_t^{[k]} \le p_{\max} \tag{19}$$

Part 1:

If the summation of the user's transmitted power is equal to $p_{\max}$ ($2p_t^{[1]}+\sum_{k=2}^{K}p_t^{[k]}=p_{\max}$), the fraction's denominator in (19) is constant. Therefore, we can optimize the fraction's numerator instead of the total fraction. The denominator $SNR^{[1]}$ in (19) includes the optimization parameter, and it's difficult to obtain the closed-form solution. To simplify the problem, an appropriate approximation is utilized in the form of $SNR^{[1]}$ as follows.

We can divide the numerator and denominator of $SNR^{[1]}$ into $p_t^{[1]}$. Since $p_t^{[R]}=p_t^{[S]}=p_t^{[1]}$ we can rewrite $SNR^{[1]}$ as (20).

$$SNR^{[1]}=\frac{p_t^{[1]}\,|h_2|^2|h_1|^2\,d_{SR}^{-\alpha}d_{RD}^{-\alpha}}{|h_2|^2\,d_{RD}^{-\alpha}\sigma^2+|h_1|^2\,d_{SR}^{-\alpha}\sigma^2+\dfrac{\sigma^4}{p_t^{[1]}}} \tag{20}$$

In $\sigma^4/p_t^{[1]}$, $p_t^{[1]}$ is approximated by $p_{t-\min}$, so we can represent $SNR^{[1]}=p_t^{[1]}\gamma$ that γ is expressed as

$$\gamma=\frac{|h_2|^2|h_1|^2\,d_{SR}^{-\alpha}d_{RD}^{-\alpha}}{|h_2|^2\,d_{RD}^{-\alpha}\sigma^2+|h_1|^2\,d_{SR}^{-\alpha}\sigma^2+\dfrac{\sigma^4}{p_{t-\min}}} \tag{21}$$

Accordingly, the EE problem is rewritten as (22).

$$\begin{aligned}&\max_{p_t^{[1]},\dots,p_t^{[k]}}\ \log_2\left(1+p_t^{[1]}\gamma\right)+\sum_{2}^{K}\log_2\left(1+p_t^{[k]}\frac{d_k^{-\alpha}|h_{k+1}|^2}{\sigma^2}\right)\\&p_t^{[1]}\ge p_{t\_\min},\,p_t^{[k]}\ge 0\quad k=2,\dots,K\\&2\times p_t^{[1]}+\sum_{k=2}^{K}p_t^{[k]}\le p_{\max}\end{aligned} \tag{22}$$

The closed-form solution of (22) is calculated as (23).

$$\begin{aligned}&p_t^{*[1]}=\left(\frac{1}{2\upsilon\ln 2}-\frac{1}{\hat{\gamma}}\right)^{+}+p_{t\_\min}\\&p_t^{*[k]}=\left(\frac{1}{\upsilon\ln 2}-\frac{\sigma^2}{d_k^{-\alpha}|h_{k+1}|}\right)^{+},k=2,\dots,K\end{aligned} \tag{23}$$

where υ should be satisfied

$$\begin{aligned}&2\left(\left(\frac{1}{2\upsilon\ln 2}-\frac{1}{\hat{\gamma}}\right)^{+}+p_{t\_\min}\right)+\\&\qquad\sum_{k=2}^{K}\left(\frac{1}{\upsilon\ln 2}-\frac{\sigma^2}{d_k^{-\alpha}|h_{k+1}|}\right)^{+}\le p_{\max}\end{aligned} \tag{24}$$

And $\hat{\gamma}$ is denoted as

$$\hat{\gamma}=\frac{\gamma}{1+P_{t\_\min}} \tag{25}$$

Proof: **See Appendix A**

In part1, When $2p_t^{[1]}+\sum_{k=2}^{K}p_t^{[k]}=p_{\max}$ the solution of (19) is different from the solution of (16). This is because in (16), the transmitted power of relay and source is $p_{t\_\min}$ while it can be more than $p_{t\_\min}$ in (19).

When SNR is low, $2p_t^{[1]}+\sum_{k=2}^{K}P_t^{[k]}=p_{\max}$ it can be satisfied after optimization (16). Thus, part1 can be appropriate to obtain the optimum solution. However, when SNR becomes higher, $2p_t^{[1]}+\sum_{k=2}^{K}p_t^{[k]}$ it can be smaller than $p_{\max}$ to maximize the network's EE. Thus, the water-filling strategy is not suitable. We will obtain the optimal solution of (19) by fractional programming as in part 2 and theorem 1.

Part 2:

In this part, we solve problem (19) by the fractional programming method [40]. Accordingly, we should optimize (26) instead of (19).

$$\begin{aligned}f(\lambda)=&\max_{p_t^{[1]},\dots,p_t^{[k]}}\log_2(1+SNR^{[1]})+\sum_{k=2}^{K}\log_2\Big(1+P_t^{[k]}\frac{d_k^{-\alpha}\,|h_{k+1}|^2}{\sigma^2}\Big)\\&\qquad-\lambda\left(\left(K+1\right)\left(p_{ct}+p_{cr}\right)+2p_t^{[1]}+\sum_{k=2}^{K}p_t^{[k]}\right)\\&p_t^{[k]}\ge 0,\,p_t^{[1]}\ge p_{t\_\min},k=2,\dots,K\\&2p_t^{[1]}+\sum_{k=2}^{K}p_t^{[k]}\le p_{\max}\end{aligned} \tag{26}$$

In (26), we consider $SNR^{[1]}=p_t^{[1]}\gamma$ like part 1. The optimum solution of (26) is obtained as (28) by KKT conditions. But $2p_t^{[1]}+\sum_{k=2}^{K}p_t^{[k]}\le p_{\max}$ constraint is still present.

$$\begin{aligned}&p_t^{*[1]}=\max\left\{\frac{1}{2\lambda\ln 2}-\frac{1}{\gamma},p_{t\_\min}\right\}\\&p_t^{*[k]}=\max\left\{\frac{1}{\lambda\ln 2}-\frac{\sigma^2}{d_k^{-\alpha}|h_{k+1}|},0\right\},k=2,\dots,K\end{aligned} \tag{27}$$

The optimum is obtained by substituting (27) in (26) and solving the equation. When $p_t^{*[k]}$ ($k=2,\dots,K$) is all expressed as $\frac{1}{\lambda\ln 2}-\frac{\sigma^2}{d_k^{-\alpha}|h_{k+1}|}$ and $p_t^{*[1]}$ is expressed as

$$\lambda^*=\frac{K\varphi\left(\dfrac{\ln 2}{eK}\left(\dfrac{\gamma}{2\ln 2}\displaystyle\prod_{k=2}^{K}\dfrac{d_k^{-\alpha}|h_{k+1}|^2}{\sigma^2\ln 2}\right)^{\frac{1}{K}}\left((K+1)(p_{ct}+p_{cr})-\dfrac{2}{\gamma}-\displaystyle\sum_{k=2}^{K}\dfrac{\sigma^2}{d_k^{-\alpha}|h_{k+1}|^2}\right)\right)}{\left((K+1)(p_{ct}+p_{cr})-\dfrac{2}{\gamma}-\displaystyle\sum_{k=2}^{K}\dfrac{\sigma^2}{d_k^{-\alpha}|h_{k+1}|^2}\right)\ln 2} \tag{28}$$

$\frac{1}{2\lambda \ln 2} - \frac{1}{\gamma}$ the equation $f(\lambda) = 0$ is difficult to solve and λ^* can be calculated as (28). When the sum of all $p_t^{*[k]}$ is 0, and $p_t^{*[1]} = p_{t\_\min}$ in (27), $f(\lambda) = 0$ it is easier to solve.

Theorem 1:

In the end, we should apply the constraint $2p_t^{[1]} + \sum_{k=2}^{K} p_t^{[k]} \le p_{\max}$; therefore, according to part 1 and part 2, the closed-form solution of (19) can be discussed as:

1. If $2p_t^{*[1]} + \sum_{k=2}^{K} p_t^{*[k]} < p_{\max}$, the closed-form solution of (19) can be defined as (28) because the constraint is always satisfied.
2. If $2p_t^{*[1]} + \sum_{k=2}^{K} p_t^{*[k]} \ge p_{\max}$, $2p_{t\_\min} \le p_{\max}$, the Closed-form solution of (19) can be defined as (22).
3. If $2p_{t\_\min} \ge p_{\max}$, all of the constraints in (19) cannot be satisfied simultaneously thus, the problem doesn't have any solutions. In this case, the total power is allocated to the source and relay of the PU.

The maximizing EE power allocation problem is represented as Algorithm 2.

IV. SIMULATION

In this section, the results are illustrated. Each transmitter sends 1 data stream to its corresponding receiver. The Rayleigh block fading is adopted, and the perfect CSI is available at all nodes. The distance between the nodes is defined as $d_{RD} = d_{SR} = 0.5, d_{SD} = d_k = 1$ except in Fig.2) and the attenuation factor is 6.

Here, we will show the performance of the SR technique in the PU and the result of the proposed power allocations algorithms. We used the following conventions to label the curves in the plots: ***SRPU*** indicates the successive relay primary user. In ***Half-duplex*** mode, the PU uses just one half-duplex relay. ***Simple PU*** implies the primary user with only one transmitter and receiver (without relay). ***EEPA*** denotes the optimum power allocation for maximizing the EE of the network. ***SRPA*** and ***Eq PA*** indicate the optimum power allocation for maximizing the sum rate of SUs and the equal power allocation considering the PU's QoS, respectively.

At first, we want to show the effect of the SR technique in PU in the absence of the SUs when IRI still exists and all nodes have a single antenna. According to the previous sentence, (1) and (2), the SINR in the destination can be obtained as (29).

Where h_{12} and $d_{R_1R_2}$ are the IRI channel coefficient and the distance between the relays, respectively. We also consider μ as an IRI suppression coefficient (by any means) to show the changes by IRI values. Thus, we plot Fig. 2.

We assume that $p_t^{[s]} = p_t^{[r]}$, $d_{SR_1} = d_{R_1D} = 1/\sqrt{2}$, $d_{R_1R_2} = 1$ and $d_{SD} = 1$. In Fig. 2, the rate of the PU is plotted according to (29) for various μ . $\mu = 0$ indicates that IRI entirely exists, $\mu = 0.9$ means 0.9 of IRI is eliminated and $\mu = 1$ means IRI is wholly eliminated.

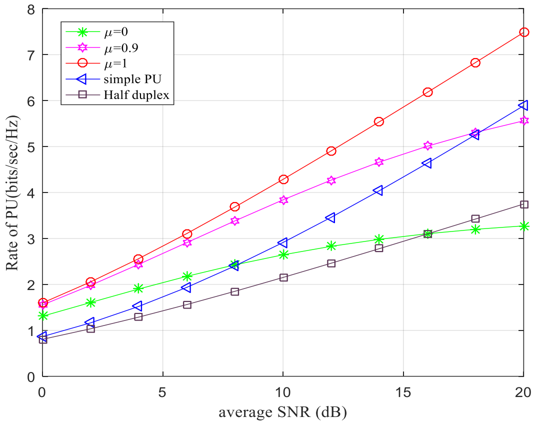

Fig. 2. Rate of PU in *Half-duplex* Mode, *Simple PU*, and *SRPU* for Various μ

Also, the rate of the PU in *simple PU* and *Half-duplex* mode is plotted. We can see that rate of the PU is upper than *Half-duplex* mode and *Simple PU* even when IRI is completely existed (in low average SNR). Moreover, the rate is more increased when IRI suppression is employed. Thus, it's better to utilize the IA technique to eliminate the IRI, especially when SUs are present.

Algorithm 2 (EEPA)

```
$p_{t\_\min}$ is calculated according to (14).
if $2p_{t\_\min} < p_{\max}$ , then
    Solve the EE power allocation problem in (19) through fractional programming according to theorem 1.
else
    Allocate $p_{\max}$ to the PU.
    SUs are switched into sleep mode.
end if
Transmission for duration T with the power allocated.
The time slot ends.
```

In Fig. 3, we compare the minimum required transmitted power of the PU to satisfy its Qos in *SRPU* and *Simple PU*. We assume and compare their PU's minimum required transmitted power and their rates in both cases. $2p_{t\_\min}/\sigma^2$ is plotted by considering (15) for the *SRPU* while $p_{t\_\min}/\sigma^2$ ($p_{t\_\min}$ is obtained in [38]) is plotted for the *Simple PU*. In both cases, the minimum required transmitted power varies dramatically over 200 time slots to guarantee the threshold rate of the PU ($R_{th}^{[1]}$). As shown in Fig.3b $R_{th}^{[1]}$ is achieved in both cases, but, as shown in Fig.3a in the *SRPU*, lower power is required ($2p_{t\_\min}$) compared to the *Simple PU*. In the *SRPU*, the minimum required power is lower than $p_{\max}$ most time slots. Thus, the SUs can use the PU's spectrum in most time slots. As shown in Fig. 3a, the largest value of $p_{t\_\min}$ is 1000 times more than its smallest value.

Consequently, if equal transmitted power is allocated to the users, the transmitted power of the PU may be much greater than its required power.

$$SINR^{[1]} = \frac{p_t^{[R]} p_t^{[S]} |h_{22}|^2 |h_{11}|^2 d_{R_1D}^{-\alpha} d_{SR_1}^{-\alpha}}{(\sigma^2 + p_t^{[R]} |h_{22}|^2 d_{R_1D}^{-\alpha}) + (\sigma^2 + (1-\mu) p_t^{[R]} |h_{12}|^2 d_{R_1R_2}^{-\alpha}) + p_t^{[S]} |h_{11}|^2 d_{SR_1}^{-\alpha} \sigma^2} \quad (29)$$

The opposite of this situation may also happen when the power of the PU is smaller than its required power. Therefore, both cases decrease the performance of the SUs and PU, respectively. Optimum power allocation can increase the performance of the SUs while guaranteeing the QoS of the PU.

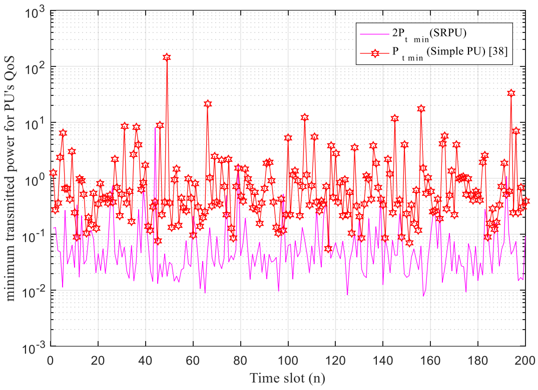

Fig. 3a. Minimal Transmitted Power of the PU to Guarantee the PU's QoS over 200 Time Slots

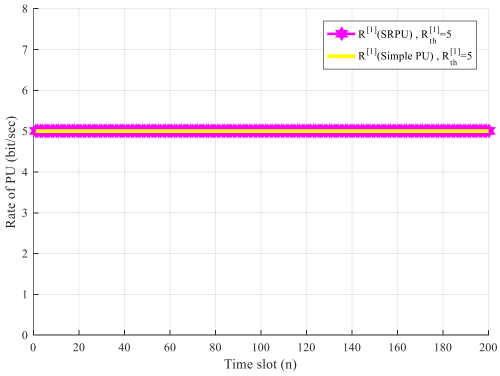

Fig. 3b. Rate of the PU over 200 Time Slots with Threshold Rate $R_{th}^{[1]} = 5$ bits/s/Hz

In Fig. 4 and Fig. 5, we assume $p_{\max} = K \times 0.1w$ and $K=3$.

In Fig. 4, the effect of the SR technique in the sum rate of the SUs is shown. In the *Simple PU*, the minimum required transmitted power of the PU is more than or equal to the network's total power in low SNR ($p_{t\_\min} \geq p_{\max}$), including 0-5 dB. Thus, $p_{\max}$ is only allocated to the PU, then the SUs must be off. As shown in Fig. 4, the sum rate of the SUs is equal to zero. When the SR technique is employed in the PU, in most of the time slots, $2p_{t\_\min}$ is lower than $p_{\max}$. Therefore, more power is allocated to the Sus and their sum-rate increases. In high SNR, due to the excellent channel conditions, the required powers of the PU in the *simple PU* and *SRPU* are very low and almost equal. Thus the sum rates of SUs in both cases are equal.

In Fig. 6 and Fig. 7, we assume that $p_{ct} = p_{cr} = 0.05W$.

Fig. 6 shows the EE of the network for *SRPU* and *Simple PU* in various $p_{\max}$. As shown in Fig. 6, by increasing $p_{\max}$ the EE of the network is decreased because of the Logarithmic property. In poor channel conditions, $p_{\max}$ is all allocated to the users, so the EE of the network is low. The EE of the network becomes higher by the SR PU in low SNR. This is because the relay cooperates with the source for transmission, and lower power is required. For example, in constant $p_{\max}$ and high SNR, SNR=30 dB, a little power $p_{\max}$ is allocated to the users. Accordingly, the total transmitted power of the users in both the *SRPU* and *Simple PU* is low and almost equal. Thus, the total circuit power consumption of the devices is determinative to compare the cases, especially in low $p_{\max}$. Due to using the relay in the PU, the circuit power consumption is increased. So in this situation, Simple PU (not using relay) is better, and the EE is higher. As shown in Fig. 6, in higher $p_{\max}$, the SR technique performs better in more regions of the SNR.

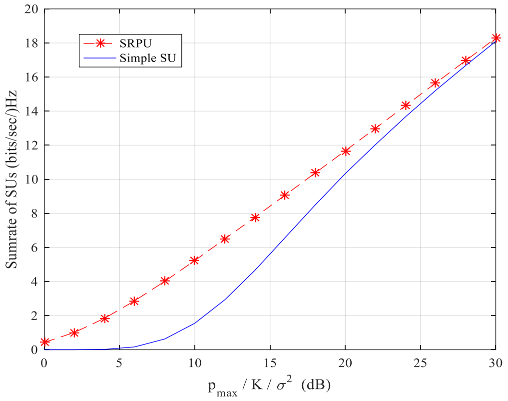

Fig. 4. The Sum Rate of SUs in the *SRPU* and *Simple PU*

Fig. 5 shows the performance of the proposed power allocation algorithm to maximize the sum rate of the SUs (Algorithm 1). The proposed power allocation improves the sum rate of SUs while satisfying the PU's QoS. The PU's QoS assurance is also considered in our simulation when equal power allocation is applied.

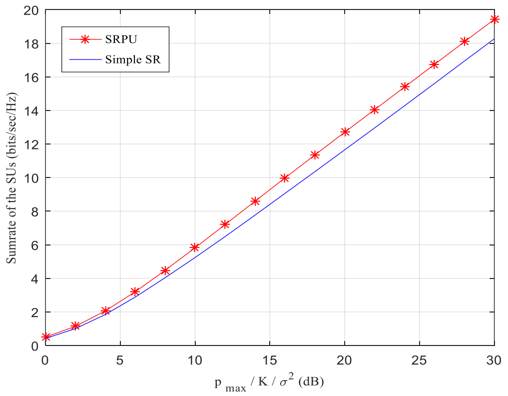

Fig. 5. The Sum Rate of SUs in *Opt SUPA* and *Eq PA* for the *SRPU*

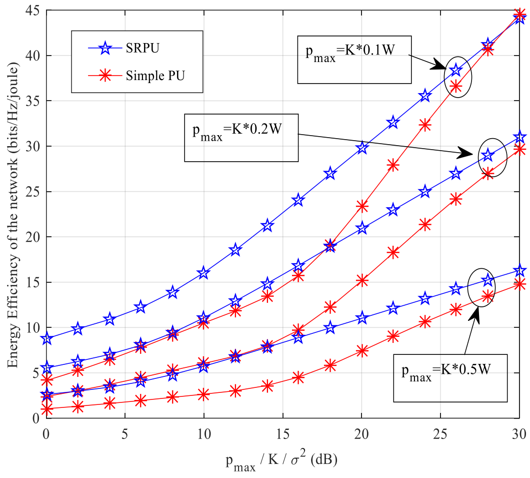

Fig. 6. The EE of the Network in *SRPU* and *Simple SR* for Various $p_{\max}$

Fig. 7 shows the EE power allocation algorithm (algorithm 2) for $p_{\max} = 1\,W, p_{\max} = 0.4W$ *K=2*. As shown in the figure, the energy efficiency of the network is increased in high SNR. Also, in high, $p_{\max}$ the effect of power allocation is more than the lower one. In Fig. 7, we plot the EE power allocation problem (19) to indicate the result without approximation.

Therefore, we can see that the closed-form solution (obtained with the approximation) equals the numerical result. As shown in the figure, the approximation is appropriate in high SNR. But in lower SNR, including 10 dB, numerical and closed-form results are slightly different. If equal powers (PU's QoS is also considered) are assigned to the users, $p_{\max}$ is all consumed in the network, and EE is reduced.

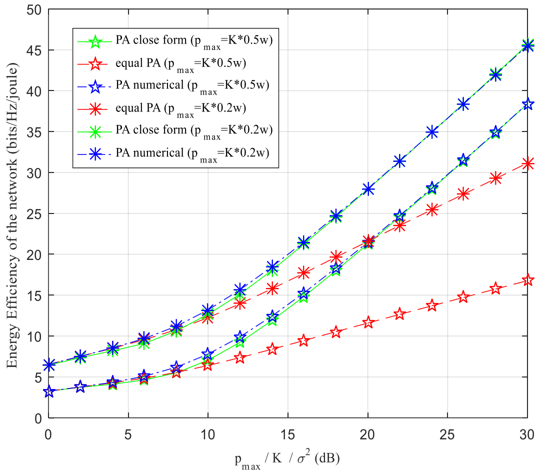

Fig. 7. The EE of the Network in *Eq PA*, *EEPA*, and Numerical Power Allocation for *SRPU*

In Fig. 8 and Fig. 9, we assume $R_{th} = 7$ $p_{\max} = 1W$ the number of users is 3, and the PU has employed the SR technique. In these figures, we plot the energy efficiency of the network and the sum rate of the SUs by two proposed algorithms. Fig. 8 indicates that the sum rate of Sus in the *SUPA* algorithm is upper than the sum rate of Sus in the *EEPA* algorithm. This is because the transmitted power of users has decreased to increase energy efficiency in *EEPA*. Accordingly, Fig. 9 shows that the energy efficiency of the network in the *EEPA* algorithm is upper than the energy efficiency of the network in the *SUPA*. But, the comparison of both figures shows that by serving the EEPA algorithm, we will significantly improve energy efficiency while ignoring the small amount of SU's sum rate.

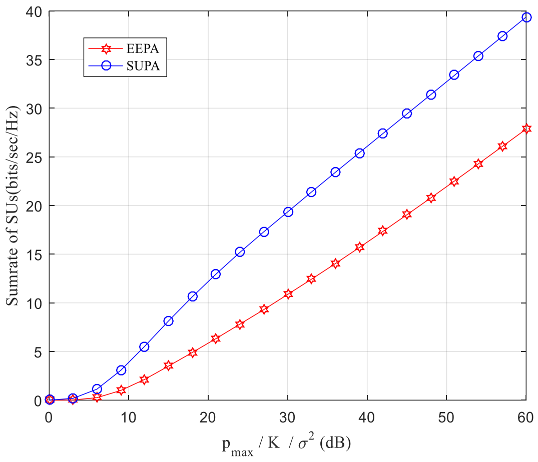

Fig. 8. Sum Rate of SUs by *EEPA* and *SUPA* Algorithms

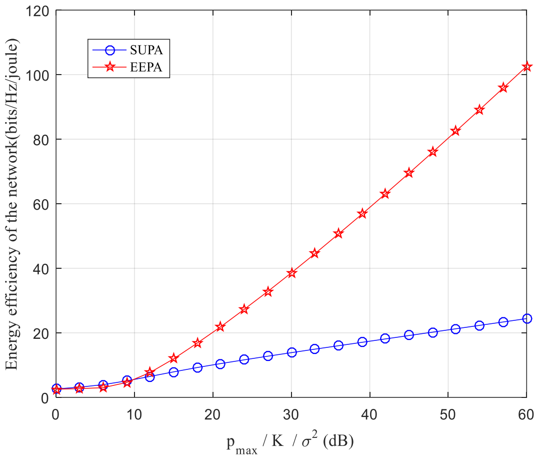

Fig. 9. Energy Efficiency of the Network by *EEPA* and *SUPA* Algorithms

V. *Conclusions*

This paper proposes a cooperative cognitive radio network that the primary user utilizes the SR technique. The IA method has been adopted to eliminate the interference (IRI in the SR and CRN interference). Then, a threshold rate has been defined for the primary user to satisfy its QoS. Accordingly, we have obtained the minimum required transmitted power for the source and the relay to satisfy the QoS of the PU. We have proposed two power allocation problems to increase the secondary users' sum rate and the network's energy efficiency. We have derived the closed-form solution for these problems. Next, we have expressed them as two algorithms. Finally, we have illustrated the obtained results. We have shown the improvement of the proposed network performance. Besides, we have shown that the SR technique in the PU has decreased the minimum transmitted power of PU. Consequently, the sum rate of secondary users and energy efficiency of the network has been increased. Also, we have proved that using the power allocations algorithms has improved the sum rate of secondary users and the energy efficiency of the network.

APPENDIX

Proof: when $2p_t^{[1]}+\sum_{k=2}^{K}p_t^{[k]}=p_{\max}$ we have

$$2P_c+2p_t^{[1]}+\sum_{k=2}^{K}p_t^{[k]}+P_c=2P_c+\sum_{k=2}^{K}P_c+p_{\max}=cte\,.$$

We also define $\hat{p}_t^{[1]}=p_t^{[1]}-p_{t\_\min}$ so we can rewrite (19) as (22) and then (30).

$$\begin{aligned}
&\max_{p_t^{[1]},\dots,p_t^{[k]}} \log_2\left[\left(1+p_{t\_\min}\right)\left(1+\hat{p}_t^{[1]}\hat{\gamma}\right)\right]+\sum_{2}^{K}\log_2\left(1+p_t^{[k]}\frac{\left|h_k\right|^2}{\sigma^2}\right)= \\
&\log_2\left(1+p_{t\_\min}\right)+\log_2\left(1+\hat{p}_t^{[1]}\hat{\gamma}\right)+\sum_{2}^{K}\log_2\left(1+p_t^{[k]}\frac{\left|h_k\right|^2}{\sigma^2}\right) \\
&=\log_2\left(1+\hat{p}_t^{[1]}\hat{\gamma}\right)+\sum_{2}^{K}\log_2\left(1+p_t^{[k]}\frac{\left|h_k\right|^2}{\sigma^2}\right) \\
&st. \quad \hat{p}_t^{[1]}\geq 0, p_t^{[k]}\geq 0 \quad k=2,\dots,K \\
&\qquad 2\hat{p}_t^{[1]}+\sum_{k=2}^{K}p_t^{[k]}\leq p_{\max}-2p_{t\_\min}
\end{aligned} \tag{30}$$

Where $\hat{\gamma}$ is expressed as (25). The optimization problem in (29) is similar to the power allocation problem in multiple parallel channels. As a result, the water-filling method can be leveraged to obtain the closed-form optimal solution. Thus, when $2p_t^{[1]}+\sum_{k=2}^{K}p_t^{[k]}=p_{\max}$ the closed-form solution of (22) is denoted as (23) and υ should satisfy (24).

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