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Rate Splitting Multiple Access Scheme for Cognitive Radio Network

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ABSTRACT

This work is the first to introduce the rate splitting multiple access (RSMA) scheme for cognitive radio (CR) networks. The particle swarm optimization (PSO) is applied to get the best beamforming vectors and common rate vectors that achieve the maximum energy efficiency (EE). It is assumed that arbitrary numbers of primary users (PUs) and secondary users (SUs) exist in the system. The proposed system design is based on the application of the optimization process as described above while maintaining the constraint that the signal-to-interference-plus-noise ratio (SINR) for any PU shall be greater than a specified minimum value. In this way, not only the SINR at any PU is maintained higher than a pre-set minimum value to ensure higher priority than any other SU but also the fairness between the PUs themselves is realized to a satisfactory level. The effects of the operational parameters in CR networks such as the number of PUs and SUs, the number of transmitting antennas, the efficiency of the power amplifier, and the dynamic power consumed by a transmitting antenna are numerically investigated.

1. Introduction

In recently, the population in the mobile internet and the internet of things (IoT) and the resulting ultra-density and heterogeneity of the forthcoming fifth-generation (5G) and sixth-generation (6G) devices in wireless networks is continuously and rapidly increasing. Thus the corresponding energy cost rises rapidly and becomes a significant challenge to sustainable development.

Also, the rapid development of progressed multimedia applications such as augmented reality (AR) and virtual reality (VR) that require broadband and high rate[1], and the fixed spectrum assignment policy result in increasingly severe spectrum scarcity problem. According to 3GPP, The fifth-generation (5G) is required to achieve high system capacity, high spectral efficiency (SE), high energy efficiency (EE), and high connectivity density[2]. Thus, it is important to develop advanced communication techniques to achieve these requirements. As one promising technique of improving the SE, cognitive radio (CR) techniques have been investigated for decades. The cognitive radio network (CRN) is a communication network that is able to alter its transmitter parameters according to the interaction with the operational environment. CRN permits the dynamic allocation of the spectrum to meet consumer demand, if a band is further used by a certified person, the cognitive radio moves to another band or stays within the identical band with changing its transmission energy or modulation scheme to mitigate interference[3]. Regarding the priority of assigning the radio frequency spectrum in cognitive radio (CR) networks, two types of users can be served under some specific constraints. These types are the

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primary users (PUs) and secondary users (SUs). Usually, the SUs are allowed to use the channel spectrum in such a way that no significant interference is caused by them on the PUs [4].

Also, multiple access (MA) schemes can play an important role in achieving energy efficiency and spectral efficiency. By novel MA techniques, the interference that occurs while serving multiple users can be handled effectively. Non-orthogonal MA (NOMA) has been recognized as a promising MA scheme for 5G and beyond cellular communication technologies because of its capability of supporting high spectral efficiency (SE) and massive connectivity. Unlike orthogonal MA (OMA), NOMA provides simultaneous access to multiple users simultaneously and on the same frequency band with different power levels [5]. However, NOMA may not be the optimal MA scheme due to its drawbacks in practical applications such as user pairing, decoding order, and interference, which require mitigation techniques that increase system complexity[6].

This leads to the necessity of developing new efficient multiple access techniques. The rate-splitting multiple access (RSMA) scheme is a promising solution for the massive connectivity problem and the rapidly increasing energy cost in wireless communication networks. In the context of the state-of-the-art multiple access techniques, the RSMA gives the best performance as regards the energy efficiency when compared to the other multiple access technique [7-10].

The RSMA scheme is based on the concept of rate-splitting and linear precoding of messages in multi-user communication system with base station of multi-antennas. In RSMA scheme, the user message is split into common and private parts. The common part of the user message is encoded in one or more common streams. On the other hand, the private part of the user message is encoded into a separate stream. After precoding, the streams can then be transmitted over multi-input single-output (MISO) channel. Each receiver decodes the common stream and decodes its private stream. The RSMA allows the interference to be partially decoded and partially treated as noise [7, 11-14].

As we proposed in [15] to apply RSMA in CRN , This work proposes a novel method to optimize the RSMA scheme for cognitive CRNs. In cognitive radio networks, the system should be able to distinguish between PUs and SUs. Irrespective of the mechanisms and the essential parameters used to distinguish between the PUs and SUs, the RSMA proposed for CR networks is optimized by searching for the optimum beamforming and common rate vectors to maximize the energy efficiency (EE).

2. RSMA System Model

Consider the downlink of MISO system where a base station with N_t transmitting antennas serves K users each of a single antenna.

2.1. Transmitted Signals by the Base Station Antennas

At the base station, the message W_k ∀k∈ {1,2,..,K is split into a common part $W_{k,c}$ and a private part $W_{k,p}$.. The common parts $W_{1,c}$,$W_{2,c}$,..,$W_{K,c}$ are jointly encoded into a common stream s_c using a codebook shared by all the users. The private parts are encoded into the streams s_1,s_2,..,s_K. The data streams are, respectively, multiplied by the beamforming vectors

$$\mathbf{P} = [\mathbf{p}_c \quad \mathbf{p}_1 \quad \mathbf{p}_2 \quad \cdot\cdot \quad \mathbf{p}_K] \tag{1}$$

The resulting transmit signal,

$$\mathrm{x} = \mathbf{Ps} = \mathbf{p}_c s_c + \mathbf{p}_1 s_1 + \mathbf{p}_2 s_2 + \cdot\cdot + \mathbf{p}_K s_K \tag{2}$$

The common stream s_c is, first, decoded at all the users by treating the interference from the private streams s_1,s_2,..,s_K as noise.

2.2. SINR at the Network Users

The SINR of decoding the common stream s_c at user K is given as:

$$\gamma_{c,k}(\mathbf{P}) = \frac{|\mathbf{h}_k^H \mathbf{p}_c|^2}{\sum_{k=1}^{K} |\mathbf{h}_k^H \mathbf{p}_c|^2 + N_{0,k}} \tag{3}$$

Where $N_{0,k} = W\,\sigma^2{}_{n,k}$ is the additive white Gaussian noise power in Watts at user-k over the transmission bandwidth W, $\sigma^2{}_{n,k}$ is AWGN variance.

The common stream s_c is decoded and removed from the received signal by successive interface cancellation (SIC). User k decodes its desired private stream s_k by treating the interference of all the other users (j=1, 2,...., K, j≠k) as noise. Thus, the SINR of decoding the private stream $s_k$is

$$\gamma_k(\mathbf{P}) = \frac{|\mathbf{h}_k^H \mathbf{p}_k|^2}{\sum_{\substack{j=1 \\ j\neq k}}^{K} \left|\mathbf{h}_j^H \mathbf{p}_j\right|^2 + N_{0,k}} \tag{4}$$

2.3. Achievable Rates of Decoding Common and Private Messages

The achievable rate of decoding s_c at user k is given as

$$R_{c,k}(\mathbf{P}) = W \log_2\left(1 + \gamma_{c,k}(\mathbf{P})\right) \tag{5}$$

To ensure that s_c is decodable by all the k users, the common rate shall not exceed R_c (P), which is common rate shared by all the k users.

$$R_c(\mathbf{P}) = \min\{R_{c,k}(\mathbf{P});\ k = 1,2,..,K\} \qquad (6)$$

It should be noted that C_k(P) is the portion of the common rate dedicated to user k. Thus, R_c(P) can be expressed as follows.

$$R_c(\mathbf{P}) = \sum_{k=1}^{K} C_k(\mathbf{P}) \qquad (7)$$

The achievable rate of decoding s_k at user k is

$$R_k(\mathbf{P}) = w \log_2(1 + \gamma_k(\mathbf{P})) \qquad (8)$$

Where w is the bandwidth.

The achievable rate of user k is

$$R_{k,\text{tot}}(\mathbf{P}) = C_k(\mathbf{P}) + R_k(\mathbf{P}) \qquad (9)$$

2.4. Power Consumption at the Transmitter

The total power consumption at the base station can be expressed as follows:

$$P_{\text{total}} = \frac{1}{\eta_{PA}} P_{\text{tran}} + P_{\text{cir}} \qquad (10)$$

Where $P_{\text{tran}} \triangleq E\ \{\|x\|^2\}$ is the transmit power, η_{PA} is the efficiency of the power amplifier of the transmitter, and P_{cir} is the circuit power that can be expressed as follows:

$$P_{\text{cir}} = N_{\text{t}}\, P_{\text{dyn}} + P_{\text{sta}} \qquad (11)$$

Where P_{dyn} is the dynamic power consumption of one antenna, and P_{sta} is the static power consumption, which is the power consumed in the power supply, cooling systems and etc.

3. RSMA Optimization for EE Maximization in NCR Networks

The RSMA EE maximization problem for a given weight vector u which represents different service levels among users can be formulated as follows:

$$\max\ \frac{\sum_{k=1}^{K} u_k\big(C_k + R_k(\mathbf{P})\big)}{\frac{1}{\eta} P_{\text{trans}} + P_{\text{cir}}} \qquad \text{(12-a)}$$

$$\text{s.t.} \left(\sum_{k=1}^{K} C_k\right) \le R_{c,k}(\mathbf{P}), \forall k \in \{1,2,..,K\} \qquad \text{(12-b)}$$

$$P_{\text{trans}} < P_{\text{t}} \qquad \text{(12-c)}$$

$$\mathbf{c} \ge 0 \qquad \text{(12-d)}$$

Where c= [C_1, C2,..,C_K $]^T$ is the common rate vector required to be optimized with the beamforming vectors. The constraint (12-b) ensures that the common stream can be successfully decoded at all the users.

An additional constraint can be added to the EE maximization problem stated by (12) as follows.

$$\frac{\gamma_k(\mathbf{P})}{\sum_{n=1}^{K} \gamma_n(\mathbf{P})} \ge \nu_{\text{NCR}}, \forall k \in \{1, 2, .., K\} \qquad \text{(12-e)}$$

Where υ_{NCR} is a fraction whose value should be < 1/k. The additional constraint (12-e) ensures an acceptable level of fairness among the users of the network. For this purpose, it may be suitable to suggest that υ_{NCR} is equal to half the multiplication inverse of k. For non-cognitive radio networks, it may be suitable to have

$$\nu_{\text{NCR}} = \frac{1}{2K} \qquad (13)$$

4. RMSA Optimization for EE Maximization in CR Networks

Let the number of PUs in a CR network be KPU (i.e. the number of SUs is K_{PU}=K-K_{SU}). Define the vector

$$\boldsymbol{\rho} = [\rho_1, \rho_2, .., \rho_k, .., \rho_K]^T \qquad (14)$$

Where,

$$\rho_k = \begin{cases} 1, & k \text{ is index of a PU} \\ 0, & k \text{ is index of a SU} \end{cases} \qquad (15)$$

4.1. Constraint for EE maximization in RSMA-based CRNs to Protect PUs

To ensure high quality of service at each PU, the SINR at each of the PUs should satisfy the following condition.

$$\frac{\gamma_k(\mathbf{P})}{\sum_{n=1}^{K} \gamma_n(\mathbf{P})} \ge \nu_{\text{CR}}, \qquad \forall k \in \{k: \rho_k = 1\} \qquad (16)$$

Where υ_{CR} is a fraction whose value should be <1/k

It may be suitable to set υ_{CR} to be dependent on the number of active PUs as follows,

$$\nu_{\text{CR}} = \frac{1}{(K_{\text{PU}} + 1)} \qquad (17)$$

Thus, the optimization problem described by (12) for EE maximization in NCR networks employing RSMA can be modified to be suitable for CR networks by replacing the constraint (12-e) by (16).

4.2. The proposed PSO algorithm for EE maximization in RSMA-based CRNs

We propose a PSO-based method [16] to obtain the approximately optimal kth user's portion of the common rates and beamforming vectors, $\{P_C, P_K, C_K\}$.Let T_{max} and N_s , respectively, denote the maximum number of iterations and the number of particles in a swarm. Let X_n, V_n, and L^n_{best} denote the position, velocity, and local best position of particle N_s, respectively. In addition, the global best position for all particles in the swarm is denoted by g_{best}. We use inertia weight parameter w to for a velocity update and the acceleration coefficients C_1 and C_2.

The PSO algorithm that implements the problem described by (12-a through 12-d) with the additional constraint (16) for EE maximization in CR networks employing RSMA can be listed as given in Table 1.

Table 1: PSO algorithm for EE maximization in CR networks employing RSMA

```
1: Inputs: $T_{max}$ , $N_s$ ,w, $C_1$, $C_2$, $V_{max}$, and variables
   $\{X_n\}$, n =1,2,3,..........., $N_s$.
2: Set the iteration index T=1
3: Initialize the particles positions $X_n = \{P_C, P_K, C_K\}$ which
      are randomly selected and evaluate EE ($X_n$)
4: Find the index of the best particle $g_{best}$=arg max {EE
      (Xn)}   @ $1 \leq n \leq Ns$
5: Initialize local best $L^n_{best}$ to its initial position: $L^n_{best}$=
      EE ($X_n$) ∀n
6: Initialize the particle's velocity $V_n=0$   ∀ n
7: Repeat
8: For each particle =1,2 ,3,..........,$N_s$, do
9: Select random numbers $r_1^n, r_2^n$ ~U (0,1)
10: Update particle's velocity
      $V_n \leftarrow wV_n + C_1 r_1^n (L_{best}^n - X_n) + C_2 r_2^n (g_{best} - X_n)$
11: Update the position of particles: $X_n = X_n + V_n$
12: Check each element of vector $X_n$ to satisfy the
      constraints, if its elements not satisfy the constraints,
      make correction for beamforming vectors and
      common rates as explained above.
13: Evaluate EE ($X_n$)
14: Update particle's local best position:
      if EE ($X_n$)>EE ($L_{bes}^n$) then
      $L_{best}^n \leftarrow X_n$.
      End if
15: Update the global best position of the swarm:
     if EE ($X_n$ )>EE ($g_{best}$)  then
       $g_{best} \leftarrow X_n$.
      End if
16: End For
17: Update T←T+1
18: Until termination criteria is met or $T>T_{max}$
19: Outputs: Set EE ($g_{best}$)   as the maximum value of
      energy efficiency (EE) at the optimal beamforming
      vectors and common rates = $g_{best}$.
```

5. Results and Discussions

It should be noted that throughout the following presentations and discussions of the numerical results, the following operational parameters of the CR network are set to the indicated values unless otherwise specified. $K=8$, $N_t=4$, $K_{PU}=4$, $K_{SU}=4$, $\rho=[1,1,0,0,1,0,1,0]^T$,$u=[1,1,1,1,1,1,1,1]^T$,$\eta_{PA}=1.0$.

We follow the channel model in [17]. The channels are given by $h_1 = [1, 1, 1, 1]^H$, $h_k = \gamma_{ch} \times [e^{(j\ (k-1)\ (Nt-1)\ \theta ch)}]$.Where γ_{ch} controls the channel gain disparity while θ_{ch} controls the channel angle.$\gamma_{ch}=1.0$,$\theta_{ch}=2\pi/9$, $P_{dyn}=1$ W, $P_{sta}=0.5$ W, $P_t=10$ W, $N_0=1.0$ W, and w=1.0Hz. The parameters for PSO is, $T_{max}=100$, $N_s=15$, w=0.7, $V_{max}=0.2$, $C_1=1$, $C_2=2$.

5.1. Convergence of the PSO Iterations for Maximization of EE

The rate of convergence of the EE maximization results with the progressive iterations of the PSO algorithm can be shown in Fig.1. For optimization of RSMA in non-cognitive radio (NCR) network with 8 users (thus, all of them are PUs) only 40 iterations are enough for the PSO algorithm to settle down on the optimum beamforming and common rate vectors. For optimization of RSMA in CR network with 8 users (4 PUs and 4 SUs) only 50 iterations are enough for the PSO algorithm to settle down on the optimum beamforming and common rate vectors. In both cases, the iterative algorithm is fast convergent and can be considered as computationally cost effective.

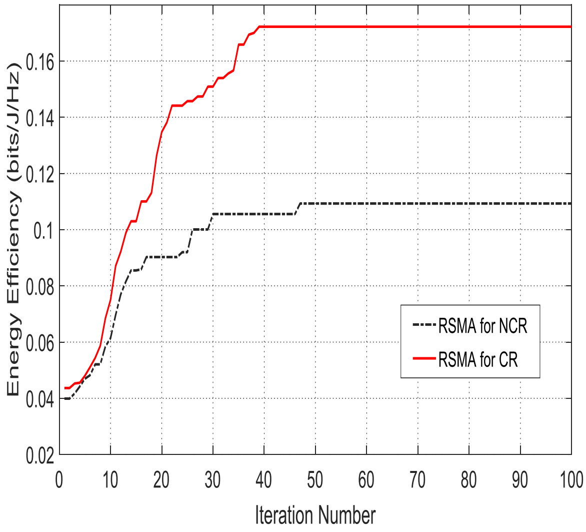

Figure 1: Convergence of the EE with the progressive iterations of the PSO in two cases: (i) NCR network with 8 users (all are PUs). (ii) CR network where the number of PUs=4 and the number of SUs=4.

It is shown that the $EE_{\max}$ reaches about 0.108 in the case of NCR network with 8 users of equal priorities. For a CR network of 8 users where 4 of them are set as PUs and the other 4 users are set as SUs, the $EE_{\max}$ reaches0.173.

5.2. Dependence of the RSMA Performance on the PA Efficiency

The dependence of the maximum EE (obtained after the application of the PSO) algorithm on the PA efficiency, η_{PA}, at the transmitter is shown in Fig.2 for three cases: (i) RSMA scheme applied in NCR network with no constraints applied on the SINR at the individual users. (ii) RSMA scheme applied in CR network where the number of Pus=4 and the number of SUs=4. (iii) RSMA scheme applied in NCR network with 8 users (all are PUs). It is shown that the $EE_{\max}$ increases with increasing the PA efficiency in the three cases.

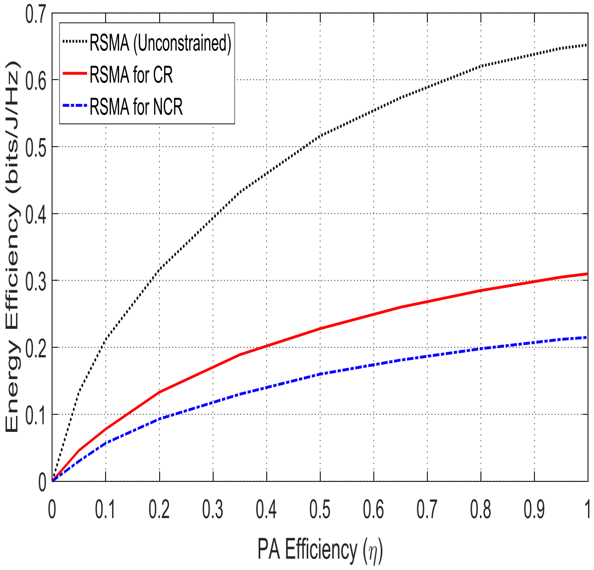

Figure 2: Dependence of the maximized EE on the PA efficiency in an optimized RSMA system for three cases: (i) No constraints applied on the SINR. (ii) CR network where the number of PUs=4 and the number of SUs=4. (iii) NCR network with 8 users (all are PUs).

The dependence of the maximum EE (obtained after the application of the PSO) algorithm on the PA efficiency, η_{PA}, at the transmitter in a CR network employing RSMA is shown in Fig.3 for different values of the channel gain. It is shown that, irrespective of the channel gain, the maximized EE increases with increasing the PA efficiency η_{PA}.

5.3. Dependence of the RSMA Performance on the Channel Gain in CR Networks

The dependence of the maximized EE, $EE_{\max}$, on the channel gain, γ_{ch}, and the PA efficiency, η_{PA}, in an optimized RSMA system for CR network where 4 PUs coexist with 4 SUs is shown in Fig.4. It is shown that $EE_{\max}$ increases with increasing the channel gain, γ_{ch}, and the PA efficiency η_{PA}.

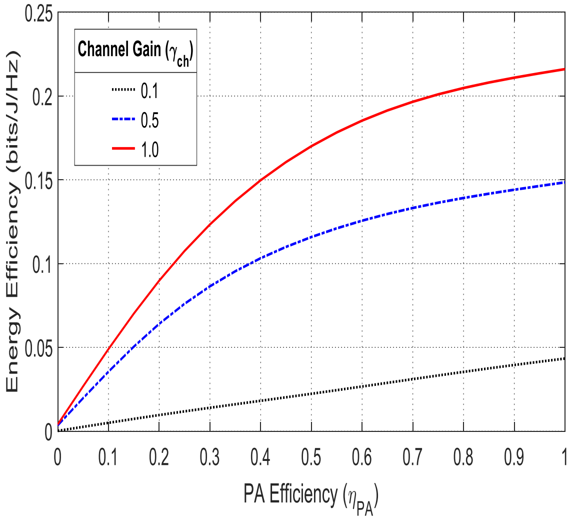

Figure 3: Dependence of the maximized EE on the PA efficiency in a CR network employing RSMA scheme for different values of the channel gain, γ_{ch}.

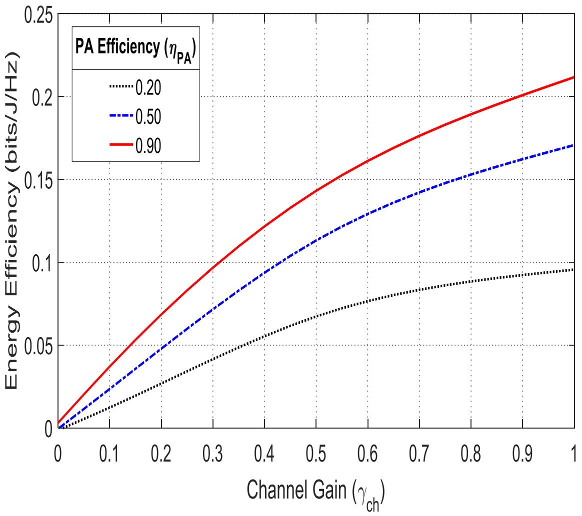

Figure 4: Dependence of the maximized EE, $EE_{\max}$, on the channel gain, γ_{ch}, and the PA efficiency, η_{PA}, in an optimized RSMA system for CR network where 4 PUs coexist with 4 SUs.

5.4. Dependence of the RSMA Performance on the Number of Transmitting Antennas and Dynamic Power Consumption

The dependence of the maximized EE, EE_{max}, on the number of transmitting antennas for different values of the dynamic power consumption, P_{dyn}, in an optimized RSMA scheme for CR network of 4 PUs and 4 SUs is shown in Fig.5. It is shown that increasing the number of transmitting antennas has the effect of decreasing EE_{max}. Also, increasing the dynamic power consumption at the transmitting leads to significant reduction of the EE_{max}. This reduction of the energy efficiency can be attributed to the increase of the total consumed power with increasing the number of transmitting antennas and the dynamic power at the antennas according to (10) and (11).

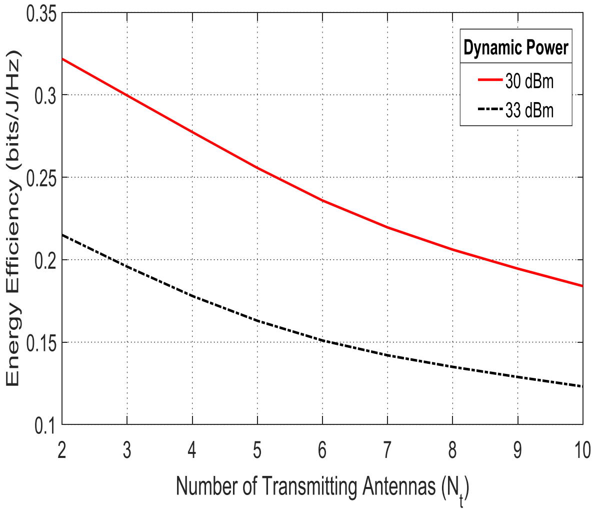

Figure 5: Dependence of the maximized EE, EE_{max}, on the number of transmitting antennas for different values of the dynamic power consumption, p_{dyn}, in an optimized RSMA scheme for CR network of 4 PUs and 4 SUs. The PA efficiency in this case is set to η_{PA}=0.9.

6. Conclusion

A novel method to optimize the RSMA scheme for CR networks has been proposed and described in detail. The PSO method is applied to get the optimum beamforming and common rate vectors to maximize the EE. Arbitrary numbers of PUs and SUs have been assumed to coexist in the system. The proposed system design is based on the application of the PSO algorithm while maintaining the constraint that the SINR for any PU is greater than a specific minimum value. In this way, not only the SINR at any PU is maintained higher than a preset minimum value to ensure higher priority than any other SU but also the fairness between the PUs themselves is realized to a satisfactory level. The effects of the operational parameters in CR networks such as the number of PUs and SUs, the number of transmitting antennas, the efficiency of the power amplifier, and the dynamic power consumed by a transmitting antenna are numerically investigated.

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