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Spectrum Resource Optimization for NOMA-Based Cognitive Radio in 5G Communications

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ABSTRACT In traditional cognitive radio (CR), secondary user (SU) can only access the idle spectrum when primary user (PU) is absent, which has to vacate the spectrum when detecting the presence of the PU. Hence, spectrum utilization of the traditional scheme is very low. Recently, nonorthogonal multiple access (NOMA) has been proposed to improve spectrum efficiency of 5G communications. In this paper, NOMA-based CR has been proposed to allow the SU to access multiple subchannels both at the absence and presence of the PU. PU-first-decoding mode (PFDM) and SU-first-decoding mode (SFDM) are proposed at the receiver to decode the NOMA signals, respectively. In the PFDM, the perfect SU throughput can be achieved, but the subchannel power has to be controlled to guarantee the PU throughput. However, in the SFDM, the SU throughput can be decreased due to the interference caused by the PU. Aiming at PFDM and SFDM, we have proposed two optimization problems, respectively, which seek to maximize normalized throughput of the SU by jointly optimizing spectrum resource including number of subchannels and subchannel transmission power. A joint optimization algorithm is proposed to solve the proposed optimization problems. The lower bound of sensing time for energy detection is then achieved to ensure spectrum sensing performance including false alarm probability and detection probability. The simulation results have shown the predominant transmission performance of the NOMA-based CR.

INDEX TERMS Cognitive radio, NOMA, spectrum resource optimization, throughput.

I. INTRODUCTION

Cognitive radio (CR) as a spectrum sharing system can improve current statistic spectrum utilization by allowing a secondary user (SU) to access idle spectrum allocated to a primary user (PU). However, the SU is not allowed to disturb the normal communications of the PU. The SU senses the idle spectrum by performing spectrum sensing which can be seen as a binary detection problem [1]–[3]. In the traditional schemes, the SU can only access the idle channel when the absence of the PU is detected and has to vacate the channel if the presence of the PU is detected. Energy detection is widely used to detect the PU through comparing the accumulated energy statistic of the PU signal to a presettled threshold. The PU is detected to be absent if the energy statistic is below the threshold [4]–[7]. The performance of energy detection is reflected by false alarm probability and detection probability. Low false alarm probability indicates highly reliable detection of the idle channel, while high detection probability means highly accurate detection on the presence of the PU. The sensing time decides the detection performance, which can be increased to decrease false alarm probability and improve detection probability [8]–[10].

Listen-before-talk spectrum access scheme was proposed in [11], in which the frame was divided into sensing slot and transmission slot and the SU could work in the transmission slot after the idle channel was detected in the sensing slot. In [12], a sensing-throughput tradeoff scheme was proposed to seek the optimal sensing time to maximize the throughput of the SU. A multichannel CR was proposed in [13], which could improve the throughput of the SU by allowing the SU to access multiple idle subchannels at the same time. In [14], power optimization of the multichannel CR was proposed to maximize the throughput of the SU at the absence of the PU. However, in the above schemes, the SU could not use the spectrum when the PU was present, thus decreasing the throughput.

Non-Orthogonal Multiple Access (NOMA) has been proposed to improve spectrum efficiency of 5G communications, which can support spectrum access of multiple users in power domain [15]–[17]. In the NOMA, multiple users can be multiplexed on the same subchannel by applying superposition coding at the transmitter and successive interference cancelation techniques at the receiver [18]–[20]. Hence, when the PU is present, the SU can also access the spectrum to improve the throughput through using NOMA. In this paper, a NOMA-based CR is proposed to access the multiple subchannels of the PU both at the absence and presence of the PU, and two kinds of decoding modes, including PU first decoding mode (PFDM) and SU first decoding mode (SFDM), are adopted at the receiver. The contributions of the paper are listed as follows:

- A NOMA-based CR is proposed to allow the SU to access the 5G spectrum both at the absence and presence of the PU. The SU can transmit data directly in the subchannel while the PU is absent and use NOMA to communicate when the PU is present. Compared with the traditional scheme, the NOMA-based CR can improve the spectrum utilization greatly.
- PFDM and SFDM are proposed to decode the NOMA signals at the receiver. In the PFDM, the PU signal is firstly decoded and reconstructed and then the SU signal is decoded by canceling the PU signal from the received signal; the PU throughput can be decreased due to the interference caused by the SU, but the SU can achieve perfect throughput. In the SFDM, the SU signal is firstly decoded and reconstructed and then the PU signal is decoded by removing the SU signal from the received signal. The SU throughput can be decreased because of the interference brought by the PU, but the PU can achieve perfect throughput.
- Aiming at PFDM and SFDM, we have proposed two optimization problems, respectively, which seek to maximize normalized throughput of the SU by jointly optimizing spectrum resource including number of subchannels and subchannel transmission power. However, in the optimization problem of PFDM, the subchannel power must be controlled to guarantee the throughput of the PU. A joint optimization algorithm is proposed to solve the proposed optimization problems.
- Sensing time selection in energy detection is investigated, and the lower bound of sensing time is achieved to ensure spectrum sensing performance including false alarm probability and detection probability. The normalized throughput under imperfect spectrum sensing is analyzed.

The rest of the paper is organized as follows. The system model is proposed in Section II, in which two kinds of decoding modes are described. In Section III, the spectrum resource optimization of PFDM is formulated as a joint optimization problem and the joint optimization algorithm is also presented. The SFDM together with its performance optimization is given in Section IV. The sensing time selection and the normalized throughput under imperfect spectrum sensing are described in Section V. The conclusions are finally drawn in Section VI.

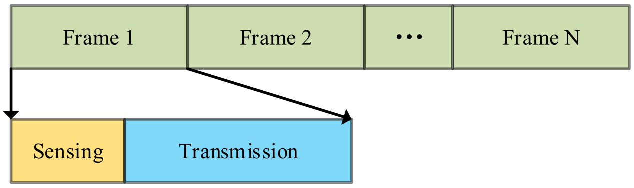

FIGURE 1. Frame structure of SU.

II. SYSTEM MODEL

We consider a SU and a PU covering N subchannels in the 5G communications, where the SU can share the spectrum with the PU without disturbing the normal communication of the PU. However, the SU can access the spectrum of the PU only when the absence of the PU is detected by spectrum sensing. The SU senses the PU periodically, which detects the PU at the beginning of each frame and then transmits in the left time of the frame, as shown in Fig. 1. In the traditional scheme, the SU directly transmits data in the subchannels when the PU is absent, but has to stop communications when the PU is present. In the paper, the SU can share the spectrum with the PU by NOMA when the PU is present. The SU and the PU transmit data in subchannel i with the power p_i and q_i, respectively. Supposing that the normalized signals of the SU and the PU are $u_i(t)$ and $s_i(t)$, respectively, the total transmission signal in subchannel i is given by $r_i(t) = \sqrt{p_i}u_i(t) + \sqrt{q_i}s_i(t)$.

As shown in Fig. 2, the receiver has two kinds of decoding modes:

- **PFDM**: The PU signal is firstly decoded and reconstructed, and then the SU signal is decoded by canceling the reconstructed PU signal from the received signal. The throughput of the SU can be guaranteed, but the throughput of the PU may be decreased due to the interference caused by the SU. In this case, the minimal throughput required by the PU must be satisfied.
- **SFDM**: The SU signal is firstly decoded and reconstructed, and then the PU signal is decoded by removing the reconstructed SU signal from the received signal. The throughput of the PU can be ensured, but the throughput of the SU will be reduced because of the interference from the PU. In this case, the throughput of the SU should be improved as much as possible.

We assume that the frame time is T, the sensing time of each subchannel is τ, the number of sensing channels is n satisfying $1 \leq n \leq N$, the transmission rates of the SU in suchannel i at the absence and presence of the PU are $R_{0,i}$ and $R_{1,i}$, respectively, and the absent and present probabilities of the PU are μ_0 and μ_1, respectively, satisfying $\mu_0 + \mu_1 = 1$. We also assume that spectrum sensing is perfect and the PU

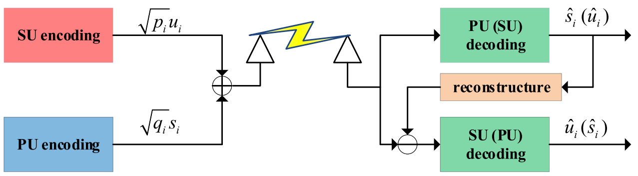

FIGURE 2. Frame structure of SU.

can be detected accurately. The normalized throughput is given as follows

$$R = \frac{T - n\tau}{T} \sum_{i=1}^{n} \left(\mu_0 R_{0,i} + \mu_1 R_{1,i}\right) \tag{1}$$

III. PU FIRST DECODING MODE

In the PU first-decoding mode, the PU signal is firstly decoded under the interference of the SU signal, and then the SU signal can be perfectly decoded by canceling the reconstructed PU signal. Thus, $R_{0,i}$ equals to $R_{1,i}$, which is given as follows

$$R_{0,i} = R_{1,i} = \log\left(1 + \frac{p_i h_i^2}{\sigma_i}\right) \tag{2}$$

where σ_i is the noise power in subchannel i and h_i is the subchannel gain between SU transmitter and receiver. Substituting (2) into (1), the throughput of the SU over n subchannels, related with n and $\{p_i\}$, is given as follows

$$R(n, \{p_i\}) = \frac{T - n\tau}{T} \sum_{i=1}^{n} \log\left(1 + \frac{p_i h_i^2}{\sigma_i}\right) \tag{3}$$

The transmission rate of the PU in subchannel i may decrease due to the interference caused by the SU, which is given as follows

$$\hat{R}_i = \log\left(1 + \frac{q_i g_i^2}{p_i h_i^2 + \sigma_i}\right) \tag{4}$$

where g_i is the subchannel gain between PU transmitter and receiver. To guarantee the transmission performance of the PU, we order that $\hat{R}_i \geq r_{min}$ where r_{min} is the minimal required rate of the PU in each subchannel. p_i is given as follows

$$p_i \leq \frac{1}{h_i^2}\left(\frac{q_i g_i^2}{2^{r_{min}} - 1} - \sigma_i\right) \tag{5}$$

Our goal is to maximize the SU throughput by jointly optimizing number of subchannels and subchannel power subject to the constraints of total power and PU throughput, which is given as follows

$$\max_{n,\{p_i\}} R(n, \{p_i\}) = \frac{T - n\tau}{T} \sum_{i=1}^{n} \log\left(1 + \frac{p_i h_i^2}{\sigma_i}\right) \tag{6a}$$

$$\text{s.t. } 1 \leq n \leq \left\lceil \frac{T}{\tau} \right\rceil, n \in [1, N] \tag{6b}$$

$$\hat{R}_i \geq r_{min}, \quad i = 1, 2, \ldots, n \tag{6c}$$

$$\sum_{i=1}^{n} p_i \leq p_{max} \tag{6d}$$

$$p_i \geq 0, \quad i = 1, 2, \ldots, n \tag{6e}$$

where $\lceil x \rceil$ denotes the maximal integer no larger than x. We use the ADO to solve the optimization problem (6). Fixing n with an integer within $\left[1, \min\left(\frac{T}{\tau}, N\right)\right]$, the optimization problem is rewritten as follows

$$\max_{\{p_i\}} F_n(\{p_i\}) = \sum_{i=1}^{n} \log\left(1 + \frac{p_i h_i^2}{\sigma_i}\right) \tag{7a}$$

$$\sum_{i=1}^{n} p_i \leq p_{max} \tag{7b}$$

$$0 \leq p_i \leq \frac{1}{h_i^2}\left(\frac{q_i g_i^2}{2^{r_{min}} - 1} - \sigma_i\right), \ i = 1, 2, \ldots, n \tag{7c}$$

which can be solved using the Karush-Kuhn-Tucker (KKT) conditions. The Lagrange function is given as follows

$$L\{p_i\} = \sum_{i=1}^{n} \log\left(1 + \frac{p_i h_i^2}{\sigma_i}\right) + \lambda\left(p_{max} - \sum_{i=1}^{n} p_i\right) \tag{8}$$

where $\lambda > 0$ is the Lagrange multiplier. p_i is obtained by $\frac{\partial L\{p_i\}}{\partial p_i} = 0$ for $i = 1, 2, \ldots, n$, which is given by

$$p_i = \left[\frac{1}{\lambda} - \frac{\sigma_i}{h_i^2}\right]^+ \tag{9}$$

Noting that the constraint (7c) must be satisfied, we can get the optimal $\{p_i^*\}$ as follows

$$p_i^* = \min\left[\frac{1}{h_i^2}\left(\frac{q_i g_i^2}{2^{r_{min}} - 1} - \sigma_i\right), \frac{1}{\lambda} - \frac{\sigma_i}{h_i^2}\right]^+, \quad i = 1, 2, \ldots, n \tag{10}$$

λ can be achieved by updating the following equation until λ is convergent.

$$\lambda^{(t+1)} = \lambda^{(t)} + \eta^{(t)}\left[p_{max} - \sum_{i=1}^{n} p_i^*\right]^+ \tag{11}$$

where t is the iteration index and $\eta > 0$ is the step length. Then the optimization algorithm about subchannel power is described in Algorithm 1. After $\{p_i\}$ is obtained, we will

Algorithm 1 Subchannel Power Optimization Algorithm

Initialize: $t = 0$, $\lambda^{(t)} > 0$ and $\eta^{(t)} > 0$;
1: with given $\lambda^{(t)}$, calculate $\{p_i^*\}$ using (10);
2: with $\{p_i^*\}$, update $\lambda^{(t+1)}$ through (11);
3: set $t = t + 1$;
4: repeat steps (1) to (3) until λ is convergent.
Output: $\{p_i^*\}$.

Algorithm 2 Joint Optimization Algorithm

Initialize: $t = 0$ and $n^{(t)}$ with any integer within $1 \sim N$;
1: with given $n^{(t)}$, calculate $\{p_i^*\}$ using Algorithm 1;
2: set $\{p_i^{(t+1)}\} = \{p_i^*\}$
3: with given $\{p_i^{(t+1)}\}$, calculate n^* using (13);
4: set $n^{(t+1)} = n^*$ and $t = t + 1$;
5: repeat steps (1) to (4) until both n and $\{p_i\}$ are convergent.
Output: n and $\{p_i\}$.

achieve the optimal n. The optimization problem is given as follows

$$\max_{n} \; R(n) = \frac{T - n\tau}{T} F_n \tag{12a}$$

$$\text{s.t. } 1 \le n \le \left\lceil \frac{T}{\tau} \right\rceil, \quad n \in [1, N] \tag{12b}$$

Since the optimal n^* makes $R(n)$ achieve the maximal value, we can get $R(n^* - 1) \le R(n^*)$ and $R(n^*) \ge R(n^* + 1)$. As F_n is nondecreasing with the increase of n, we have $F_{n+1} \ge F_n \ge F_{n-1}$. Letting $\triangle F_{n-1} = F_n - F_{n-1}$ and $\triangle F_n = F_{n+1} - F_n$, we can obtain that

$$\frac{\triangle F_{n^*-1}}{F_{n^*-1}} \ge \frac{\tau}{T - n^*\tau} \ge \frac{\triangle F_{n^*}}{F_{n^*+1}} \tag{13}$$

Since n is an integer within $1 \sim N$, it is not computationally complex to enumerate n to satisfy (13). As the throughput may improve by selecting better subchannel for transmissions, we array N subchannels in descending order of channel gains and select the front n subchannels for transmissions. In the ADO, $\{p_i\}$ and n are optimized alternatively until both of them are convergent. The joint optimization algorithm is described in Algorithm 2. Supposing the convergence precision of p_i is ϵ, with given n, the iteration complexity of calculating $\{p_i\}$ is $O\left(\frac{1}{\epsilon^n}\right)$. As optimal n can be achieved through enumeration from 1 to N, the total iteration complexity is given by $O\left(\sum_{n=1}^{N} \frac{1}{\epsilon^n}\right)$.

IV. SU FIRST DECODING MODE

In the SFDM, the SU signal is firstly decoded and reconstructed, and then the PU signal is decoded by removing the SU signal from the received signal. The PU can achieve perfect throughput due to the interference cancelation, but the SU throughput may decrease because of the interference brought by the PU. Thus, $R_{0,i}$ and $R_{1,i}$ are respetively given by

$$R_{0,i} = \log\left(1 + \frac{p_i h_i^2}{\sigma_i}\right)$$
$$R_{1,i} = \log\left(1 + \frac{p_i h_i^2}{q_i g_i^2 + \sigma_i}\right) \tag{14}$$

The normalized throughput is given as follows

$$R(n, \{p_i\}) = \frac{T - n\tau}{T} \sum_{i=1}^{n} \left(\mu_0 \log\left(1 + \frac{p_i h_i^2}{\sigma_i}\right) + \mu_1 \log\left(1 + \frac{p_i h_i^2}{q_i g_i^2 + \sigma_i}\right)\right) \tag{15}$$

Our goal is to maximize the SU throughput subject to the constraint of total power, which is given by

$$\max_{n,\{p_i\}} R(n, \{p_i\}) = \frac{T - n\tau}{T} \sum_{i=1}^{n} \left(\mu_0 \log\left(1 + \frac{p_i h_i^2}{\sigma_i}\right) + \mu_1 \log\left(1 + \frac{p_i h_i^2}{q_i g_i^2 + \sigma_i}\right)\right) \tag{16a}$$

$$\text{s.t. } 1 \le n \le \left\lceil \frac{T}{\tau} \right\rceil, \quad n \in [1, N] \tag{16b}$$

$$\sum_{i=1}^{n} p_i \le p_{max} \tag{16c}$$

$$p_i \ge 0, \quad i = 1, 2, \ldots, n \tag{16d}$$

Fixing n, the optimization problem about $\{p_i\}$ is rewritten as follows

$$\max_{\{p_i\}} F_n = \sum_{i=1}^{n} \left(\mu_0 \log\left(1 + \frac{p_i h_i^2}{\sigma_i}\right) + \mu_1 \log\left(1 + \frac{p_i h_i^2}{q_i g_i^2 + \sigma_i}\right)\right) \tag{17a}$$

$$\sum_{i=1}^{n} p_i \le p_{max} \tag{17b}$$

$$p_i \ge 0, \quad i = 1, 2, \ldots, n \tag{17c}$$

Using the KKT conditions, the Lagrange function is given as follows

$$L(\{p_i\}) = \sum_{i=1}^{n} \left(\mu_0 \log\left(1 + \frac{p_i h_i^2}{\sigma_i}\right) + \mu_1 \log\left(1 + \frac{p_i h_i^2}{q_i g_i^2 + \sigma_i}\right)\right) + \lambda\left(p_{max} - \sum_{i=1}^{n} p_i\right) \tag{18}$$

Then the optimal $\{p_i^*\}$ is calculated as follows

$$p_i^* = \left[\sqrt{\frac{1}{4\lambda^2} + \frac{q_i g_i^2}{2\lambda h_i^2}(u_0 - u_1) + \frac{q_i^2 g_i^4}{4h_i^4}} + \frac{1}{2\lambda} - \frac{q_i g_i^2 + 2\sigma_i}{2h_i^2}\right]^+ \tag{19}$$

There are two especial cases. One is $u_0 = 1$ and $u_1 = 0$, denoting that the PU is always absent, and the other one is $u_0 = 0$ and $u_1 = 1$, denoting that the PU is always present. The subchannel power in these two cases is given as follows

$$p_i^* = \begin{cases} \left[\frac{1}{\lambda} - \frac{\sigma_i}{h_i^2}\right]^+, & u_0 = 1, \; u_1 = 0 \\ \left[\frac{1}{\lambda} - \frac{q_i g_i^2 + \sigma_i}{h_i^2}\right]^+, & u_0 = 0, \; u_1 = 1 \end{cases} \tag{20}$$

We decided to adopt PFDM or SFDM through comparing average signal to noise ratio (SNR) of SU and PU at the receiver. That is, if $\frac{1}{N}\sum_{i=1}^{N}\frac{p_i h_i^2}{\sigma_i^2} \geq \frac{1}{N}\sum_{i=1}^{N}\frac{q_i g_i^2}{\sigma_i^2}$, SFDM is used at the receiver, otherwise, PFDM is adopted.

V. SENSING TIME SELECTION

The subchannel sensing time τ impacts the spectrum sensing performance of the SU directly. Energy detection is commonly used to sense the PU, which compares the energy statistic of the PU signal to a presettled threshold and decides the presence of the PU if the energy statistic is above the threshold. The sensing signal $y_i(m)$ at the SU in subchannel i is given as follows

$$y_i(t) = \begin{cases} g_i(t)\sqrt{q_i}s_i(t) + \sqrt{\sigma_i}\delta_i(t), & H_1 \\ \sqrt{\sigma_i}\delta_i(t), & H_0,\ m = 1, 2, \ldots, M \end{cases} \tag{21}$$

where $\delta_i(t)$ is the normalized noise signal, M is the number of the samplings; H_0 and H_1 denote the absence and the presence of the PU, respectively, which satisfy $P_r(H_0) = u_0$ and $P_r(H_1) = u_1$. Supposing the sampling frequency is f_s, we have $M = \tau f_s$. The energy statistic of the sensing signal is given as follows

$$\Phi(y_i) = \frac{\sum_{t=1}^{M}\|y_i(t)\|^2}{M} \tag{22}$$

Since $y_i(t)$ for $t = 1, 2, \ldots, M$ are independently and identically distributed, according to the Central Limit Theorem, $\Phi(y)$ obeys the Gaussian distribution at large M as follows

$$\Phi(y_i) \sim \begin{cases} \mathcal{N}\left((q_i g_i^2 + \sigma_i), \frac{(q_i g_i^2 + \sigma_i)^2}{M}\right), & H_1 \\ \mathcal{N}\left(\sigma_i, \frac{\sigma_i^2}{M}\right), & H_0 \end{cases} \tag{23}$$

False alarm probability and detection probability are defined to measure the spectrum sensing performance. False alarm probability denotes the probability that the energy statistic is above the threshold at H_0, which decides the spectrum utilization ability of the SU. Thus, the false alarm probability is given as follows

$$P_f = P_r(\Phi(y_i) > \rho|H_0) = Q\left(\left(\frac{\rho}{\sigma_i} - 1\right)\sqrt{\tau f_s}\right) \tag{24}$$

where ρ is the detection threshold and $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{+\infty}\exp\left(-\frac{\omega^2}{2}\right)\mathbf{d}\omega$. Detection probability indicates the probability that the energy statistic is below the threshold at H_1, which determines the ability of discovering the PU. Hence, the detection probability is obtained as follows

$$P_d = P_r(\Phi(y_i) > \rho|H_1) = Q\left(\left(\frac{\rho}{q_i g_i^2 + \sigma_i} - 1\right)\sqrt{\tau f_s}\right) \tag{25}$$

Sometimes spectrum sensing is imperfect, in which we let $P_f \leq \alpha$ and $P_d \geq \beta$ (α and β are often set as $\alpha \leq 0.5$ and $\beta \geq 0.5$). From (24) and (25), we can get that the range of sensing threshold as follows

$$\left[\frac{Q^{-1}(\alpha)}{\sqrt{\tau f_s}} + 1\right]\sigma_i \leq \rho \leq \left[\frac{Q^{-1}(\beta)}{\sqrt{\tau f_s}} + 1\right](q_i g_i^2 + \sigma_i), \quad i = 1, 2 \ldots, n \tag{26}$$

where we can get that

$$\left[\frac{Q^{-1}(\alpha)}{\sqrt{\tau f_s}} + 1\right]\sigma_i \leq \left[\frac{Q^{-1}(\beta)}{\sqrt{\tau f_s}} + 1\right](q_i g_i^2 + \sigma_i) \tag{27}$$

where the range of τ is given as follows

$$\tau \geq \max\left\{\frac{\left[Q^{-1}(\alpha)\sigma_i - Q^{-1}(\beta)(\sigma_i + q_i g_i^2)\right]^2}{q_i^2 g_i^4 f_s}\right\}_{i=1}^{n} \tag{28}$$

As the transmission time of the SU may decrease as the sensing time increases, the sensing time can be selected as the lower bound. The normalized throughput under imperfect spectrum sensing is given as follows

$$R = \frac{T - n\tau}{T}\sum_{i=1}^{n}\left(\mu_0(1-\alpha)R_{0,i} + \mu_1(1-\beta)R_{1,i}\right) \tag{29}$$

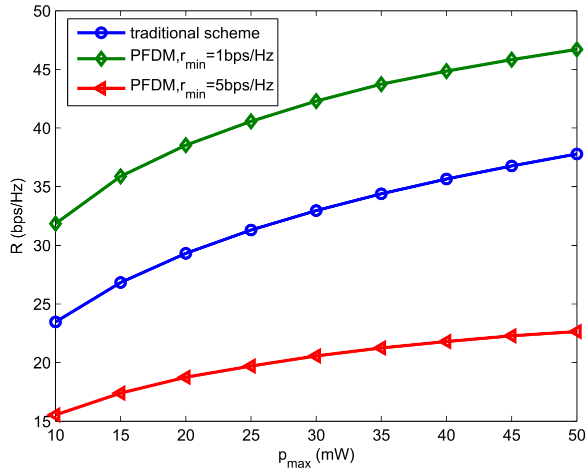

FIGURE 3. Throughput comparison between PFDM and traditional scheme.

VI. SIMULATIONS AND DISCUSSIONS

In the simulations, the total number of subchannels is $N = 40$, the frame time is $T = 1$s, the subchannel sensing time is $\tau = 20$ms, the absence and presence probabilities of the PU are $u_0 = u_1 = 0.5$, the noise power $\sigma_i = 0.01$mW, and the channels obey the Rayleigh fading.

Fig. 3 compares the throughput of the SU R between the PFDM and the traditional scheme. It is seen that the throughput of PFDM is larger than that of the traditional scheme when the minimal subchannel throughput of the PU $r_{min} = 1$bps/Hz, but less than that when $r_{min} = 5$bps/Hz. Because the SU signal is seen as the interference when decoding the PU signal, which may decrease the throughput of the PU, and thus the SU has to control the transmission power to

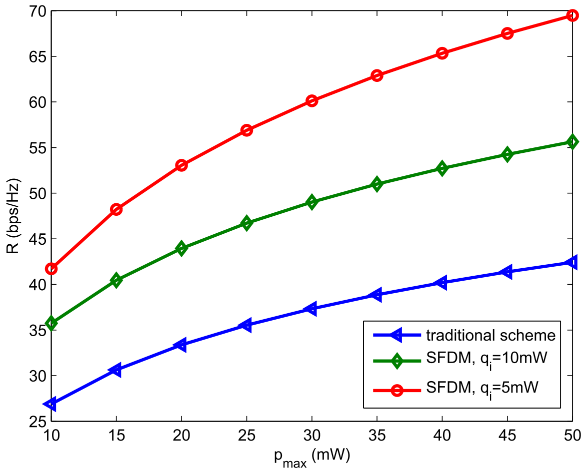

FIGURE 4. Throughput comparison between SFDM and traditional scheme.

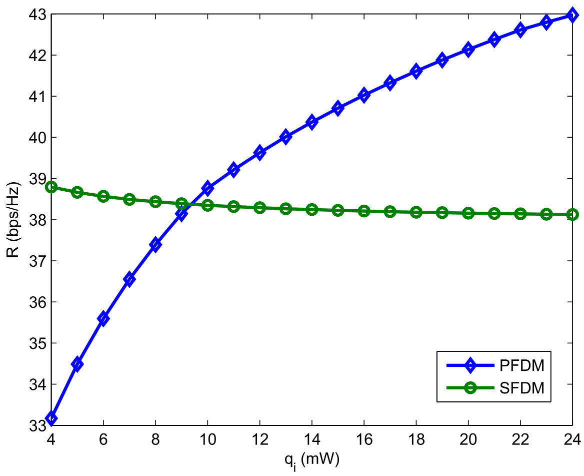

FIGURE 5. Throughput comparison between PFDM and SFDM.

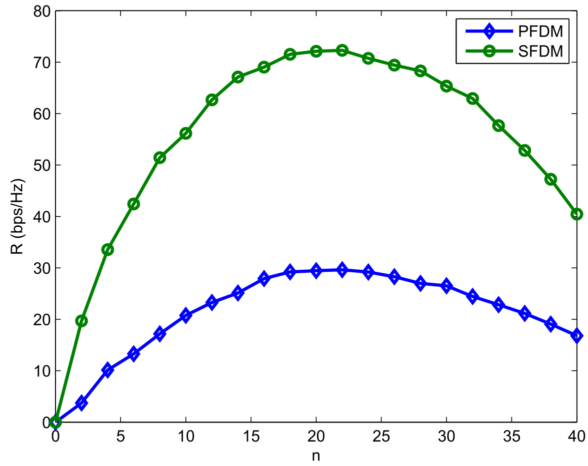

FIGURE 6. Throughout with different number of subchannels.

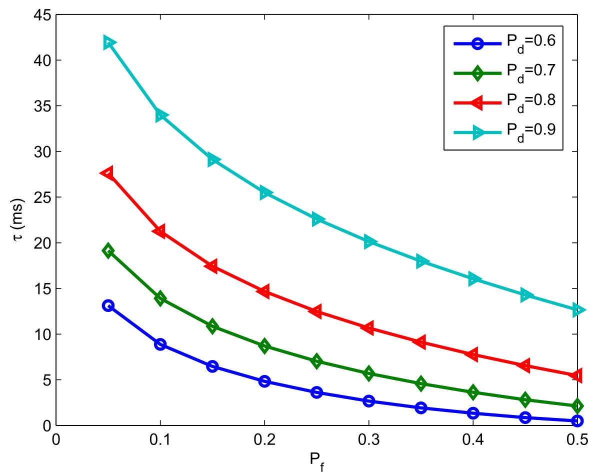

FIGURE 7. Sensing time with different false alarm probability.

guarantee the minimal throughput of the PU when r_{min} is set too large. Fig. 4 compares the throughput between the SFDM and the traditional scheme. It is seen that the throughput of the SFDM is always larger than that of the traditional scheme with any subchannel power p_i of the PU. Because the SU can access the spectrum both at the absence and presence of the PU, while the traditional scheme can only access the spectrum at the absence of the PU. The throughput of the SU decreases when the PU power increases, because in the SFDM, the PU signal can be seen as the interference when decoding the SU signal, which may decrease the SU throughput.

Fig. 5 compares the throughput between the PFDM and the SFDM. The throughput of the SFDM is larger than that of the PFDM with lower PU subchannel power, but less than that with larger PU subchannel power. Because in PFDM, the transmission power of the SU must be controlled to ensure the signal to interference ratio (SIR) at the PU receiver when q_i is small, which decreases the throughput of the SU, however, the power will not be controlled with large q_i due to the enough large SIR at the PU receiver, which improves the throughput of the SU because of the perfect SU decoding. Fig. 6 indicates the throughput of the SU with different number of subchannels n. It is seen that the throughput is less both at small and large n, because the transmission rate decreases with the decrease of n while the transmission time reduces with the increase of n. Thus, there is an optimal n to achieve the maximal throughput.

Fig. 7 shows the sensing time τ with different false alarm probability P_f. It is seen that the sensing time decreases with the increase of false alarm probability and increases with the improvement of detection probability. Thus, the sensing time has to be increased to improve the sensing performance. Fig. 8 shows the throughput of the SU with different detection probability under imperfect spectrum sensing. It is seen that the throughput decreases with the improvement of detection probability. When $P_d = 1$, the throughput arrives zero, because $P_f = 1$ at the same time. Hence, P_d should be chosen appropriately in spectrum sensing.

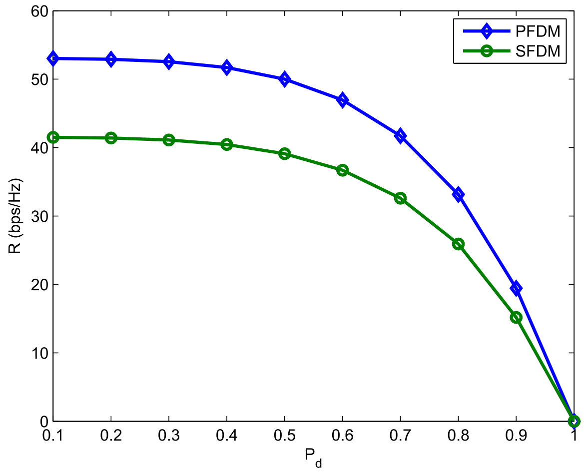

FIGURE 8. Throughput with different detection probability.

VII. CONCLUSIONS

In this paper, we have proposed a NOMA-based CR which can access the spectrum both at the absence and presence of the PU. The receiver uses PFDM and SFDM to decode the NOMA signals, respectively. In the PFDM, the SU can achieve perfect throughput but the subchannel power must be controlled to guarantee the PU throughput. However, in the SFDM, the SU throughput is decreased because of the interference caused by the PU. Aiming at PFDM and SFDM, we have proposed two optimization problems of spectrum resource, which seek to maximize the SU throughput by jointly optimizing the number of subchannels and the subchannel power. From the simulations, we have got the following conclusions:

- Compared with the traditional scheme, the throughput of the PFDM is larger at lower PU throughput but less at higher PU throughput, because the SU signal is seen as the interference when decoding the PU signal, whose subchannel power has to be controlled to guarantee the minimal throughput of the PU. However, the throughput of the SFDM is always larger than that of the traditional scheme due to higher spectrum utilization at the presence of the PU.
- The throughput of the SFDM is larger than that of the PFDM with lower PU subchannel power, but less than that with larger PU subchannel power. Because the throughput of the PFDM firstly decreases due to the power control of the SU but then improves because of the perfect SU decoding.
- The sensing time decreases with the increase of false alarm probability and increases with the improvement of detection probability. Thus, the sensing time has to be increased to improve the sensing performance.

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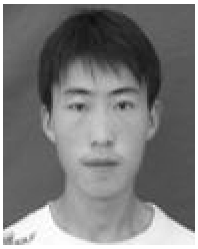

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