Statistical Delay QoS Protection for Primary Users in Cooperative Cognitive Radio Networks

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***Abstract*—In cooperative cognitive radio networks, where secondary users (SU) can relay the signal of primary user (PU) in exchange for PU's licensed spectrum, most existing works employ deterministic quality-of-service (QoS) guarantee in terms of minimum required transmission rate for PU's protection. In this letter, we adopt the statistical QoS requirement characterized by *queue-length bound violation probability* for PU's delay QoS provisioning. By applying the *effective capacity* theory, we further convert *PU's queue-length bound violation probability requirement* to the equivalent *effective capacity constraint* and formulate the corresponding SU's throughput maximization problem. Then, we obtain the optimal joint time-slot allocation scheme, where the time-slot division adapts to both channel conditions and PU's delay QoS requirements, such that not only PU's statistical delay QoS requirement can be well guaranteed, but also SU's throughput can be optimized. Moreover, we also develop a fixed time-slot allocation scheme that only varies with PU's delay QoS requirements. Simulation results show that both the optimal and fixed allocation schemes can flexibly perform time-slot divisions according to the delay QoS requirements of PU's traffic, but the developed optimal scheme outperforms the fixed time-slot allocation scheme.**

***Index Terms*—Cognitive radio, cooperative communications, statistical quality-of-service (QoS) provisioning, effective capacity.**

I. INTRODUCTION

COGNITIVE RADIO (CR), which allows secondary users (SU) to share the spectrum licensed to primary users (PU), is an promising approach to alleviate the spectrum underutilization problem [1], [2]. To avoid the interference between PU and SU, cooperative cognitive radio network (CRN), which employs the PU-SU cooperation to achieve interference-free transmission for both PU and SU, has attracted a lot of research attention in recent years [3]–[5].

However, in most existing works toward the cooperative CRNs, PU's delay quality-of-service (QoS) protection is modeled as the minimum required transmission rate [3]–[5], which can only characterize the very stringent delay requirement. Moreover, due to the time-varying feature of wireless channels, such a deterministic delay requirement usually cannot be well guaranteed. Thus, the statistical approach can be better suited for PU's delay QoS provisioning. Although statistical QoS driven resource allocation schemes for CRNs have attracted more and more research attention, all existing works only focus on performing statistical QoS guarantees for SUs, but not provide efficient delay QoS provisioning for PUs [8], [9]. Consequently, there is an urgent need to develop an efficient PU-SU cooperation framework for PU's statistical delay QoS provisioning and derive the optimal resource allocation to optimize SU's performance.

To achieve the above goals, we in this letter developed a joint time-slot allocation framework for cooperative CRNs with PU's statistical delay QoS provisioning. Specifically, our proposed framework allows SU to adaptively determine the cooperation duration based on distinct PU's delay QoS requirements characterized by *PU's queue-length bound violation probability* [6]. By applying the *effective capacity* theory [7], we formulate the SU's throughput maximization problem subject to PU's statistical delay QoS requirement and obtain the optimal joint time-slot allocation scheme, where the transmission time-slot dynamically varies according to both PU's statistical delay QoS requirements and channel conditions. To reduce the computation complexity, we also develop for comparison a suboptimal scheme named fixed time-slot allocation policy, which is adjusted only based on PU's delay QoS requirements.

II. SYSTEM MODEL

We consider a CRN coexisting with a primary network (PN) by sharing a certain spectrum band with bandwidth B. Specifically, the PN includes a primary sender (PS) and a primary receiver (PR). The CRN, which can perform cooperation with PN, includes a secondary sender (SS) and a secondary receiver (SR). In particular, the SS is allowed to relay PS's data to PR to help the PN meet its delay quality-of-service (QoS) requirement. Then, the SS-SR pair could obtain the spectrum resources licensed to the PN for their transmissions (which will be detailed in Section III).

We denote the channel power gains between PS and PR, PS and SS, SS and PR, as well as SS and SR by $h_{\rm pp}$, $h_{\rm ps}$, $h_{\rm sp}$, and $h_{\rm ss}$, respectively. Then, we can define the network gain vector (NGV) as $\boldsymbol{h} \triangleq \{h_{\rm pp}, h_{\rm ps}, h_{\rm sp}, h_{\rm ss}\}$, which are known to both PS and SS. All channel power gains that follow the Rayleigh fading model are assumed to be stationary, ergodic,

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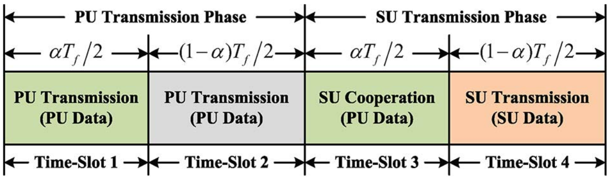

Fig. 1. Joint time-slot allocation framework for PU-SU cooperation.

independent, and block fading processes. Consequently, the NGV $\boldsymbol{h}$ remains constant within each frame with duration T_f, but varies independently from one frame to another. Moreover, we assume that both PS and SS transmit with constant power under the average power budgets P_{p} and P_{s}, respectively.

III. Joint Time-Slot Allocation Framework With PU's Statistical Delay QoS Provisioning

A. *Time-Slot Division for PU-SU Cooperation*

Our proposed time-slot allocation framework is shown in Fig. 1. Each frame with duration T_f is divided into two phases with equal duration $T_f/2$, which are PU transmission phase and SU transmission phase, respectively. Moreover, we further divide each phase into two slots, where PU transmission phase includes slots 1 and 2 and SU transmission phase includes slots 3 and 4. Specifically, slots 1 and 3 have the same length denoted by $\alpha T_f/2$, where $\alpha \in [0,1]$, and slots 2 and 4 have the equal length denoted by $(1-\alpha)T_f/2$. In slots 1 and 2, PS transmits to PR. In slot 3, SS will amplify-and-forward (AF) PS's signal in slot 1 to PR. In slot 4, SS transmits its own data to SR.

As PS's data sent in slot 1 is relayed by SS in slot 3, PS's data rate in slot 1, denoted by $R_{\mathrm{p}}^1(\alpha)$, can be written as

$$R_{\mathrm{p}}^1(\alpha)=\frac{\alpha T_f B}{2}\log_2\left(1+\frac{2P_{\mathrm{p}}h_{\mathrm{pp}}}{\sigma^2}+\frac{4P_{\mathrm{p}}P_{\mathrm{s}}h_{\mathrm{ps}}h_{\mathrm{sp}}}{\sigma^2+2P_{\mathrm{p}}h_{\mathrm{ps}}+2P_{\mathrm{s}}h_{\mathrm{sp}}}\right), \tag{1}$$

where α denotes the time-proportion of slots 1 and 3 and σ^2 represents the variance of additive white Gaussian noise (AWGN). As both PS and SS only occupy half duration of each frame, the actual transmit power of PS and SS are $2P_{\mathrm{p}}$ and $2P_{\mathrm{s}}$, respectively, under their predefined average power budgets for each frame. Without SS's relaying, PS's data rate in slot 2, denoted by $R_{\mathrm{p}}^2(\alpha)$, is determined by

$$R_{\mathrm{p}}^2(\alpha)=\frac{(1-\alpha)T_f B}{2}\log_2\left(1+\frac{2P_{\mathrm{p}}h_{\mathrm{pp}}}{\sigma^2}\right). \tag{2}$$

Consequently, the average achievable rate of PS in each frame, denoted by $R_{\mathrm{p}}(\alpha)$, is given by

$$R_{\mathrm{p}}(\alpha)=R_{\mathrm{p}}^1(\alpha)+R_{\mathrm{p}}^2(\alpha),\ \text{(bits/frame)}. \tag{3}$$

After relaying PS's data, SS could transmit to SR in slot 4. Then, SS's achievable rate, denoted by $R_{\mathrm{s}}(\alpha)$, can be written as

$$R_{\mathrm{s}}(\alpha)=\frac{(1-\alpha)T_f B}{2}\log_2\left(1+\frac{2P_{\mathrm{s}}h_{\mathrm{ss}}}{\sigma^2}\right). \tag{4}$$

Remark 1: Based on the above descriptions, we can clearly observe that our developed time-slot allocation based PU-SU cooperation mechanism is a flexible framework. Different values of α result in distinct cooperation strategies. Specifically, when $\alpha = 0$, there is *no cooperation* between PN and CRN; when $\alpha = 1$, SS is in the *full-cooperation mode*, which means that SS will relay all PS's data in the PU transmission phase; when $0 < \alpha < 1$, SS is in the *partial-cooperation mode*, i.e., only part of PS's data will be relayed.

Remark 2: The values of α will affect the performances of both PN and CRN. One one hand, we can find from (1) and (2) that $R_{\mathrm{p}}^1(\alpha) > R_{\mathrm{p}}^2(\alpha)$, which implies that PS's data rate $R_{\mathrm{p}}(\alpha)$ can be efficiently improved by SS's relaying. Moreover, the larger the value of α is, the higher PS's data rate can be achieved. However, on the other hand, (4) shows that the achievable rate of SS is the decreasing function of α. Consequently, we need to determine the optimal value of α to maximize the data rate of SS while meeting PS's delay QoS requirement.

B. *Statistical Delay QoS Provisioning for PUs*

In this letter, we perform statistical delay QoS provisioning for PUs, which is characterized by *PU's queue-length bound violation probability*. Specifically, PU's queue-length bound violation probability requires that the probability of PU's queue-length exceeding a certain threshold should be below a predefined violation probability, i.e.,

$$\Pr\{Q \geq Q_{\mathrm{th}}\} \leq P_{\mathrm{th}}, \tag{5}$$

where Q and Q_{th} denote PU's queue-length and predefined queue-length threshold, respectively, and P_{th} is the maximally allowed violation probability.

To obtain the analytical expression for $\Pr\{Q \geq Q_{\mathrm{th}}\}$, we can apply asymptotic queuing analysis and effective capacity theory to achieve the above goal. We assume that PS has constant-rate arrival process denoted by $\overline{R}_{\mathrm{A}}$ (bits/s/Hz).[1] Moreover, as PS's service rate $R_{\mathrm{p}}(\alpha)$ given by (3) is an independent and time-uncorrelated stochastic process across each frame, the queue-length bound violation probability is determined by [6], [7]

$$\Pr\{Q \geq Q_{\mathrm{th}}\} \approx e^{-\theta Q_{\mathrm{th}}}, \tag{6}$$

where θ is called the *QoS exponent*, describing the decaying speed of violation probability versus queue-length bound. By using this equation, we can easily find that, for any given queue-length threshold Q_{th} and violation probability bound P_{th}, the QoS exponent θ needs to satisfy

$$\theta \geq -\frac{1}{Q_{\mathrm{th}}}\log(P_{\mathrm{th}}). \tag{7}$$

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[1] For any given arrival rate process, which is independent and uncorrelated across each frame, we can use the effective bandwidth theory to obtain the equivalent constant data arrival rate [6]. Thus, without loss of generality, we in this letter assume a constant data arrival rate process for simplicity.

Therefore, we can use θ to describe the PU's statistical QoS requirement. Specifically, smaller θ leads to looser QoS constraint and larger θ represents more stringent QoS requirement.

Thanking to the effective capacity theory, we can convert the required *queue-length bound violation probability* to the equivalent *effective capacity constraint*. The effective capacity is defined as the maximum constant arrival rate that can be supported by the given time-varying service rate process. Thus, PS's effective capacity of the service rate process $R_{\mathrm{p}}(\alpha)$, denoted by $\mathrm{E}_{\mathrm{C}}^{\mathrm{PU}}(\theta)$ (bits/frame), is given by [7]

$$\mathrm{E}_{\mathrm{C}}^{\mathrm{PU}}(\theta,\alpha) = -\frac{1}{\theta}\log\left(\mathbb{E}_{\boldsymbol{h}}\left\{e^{-\theta R_{\mathrm{p}}(\alpha)}\right\}\right), \tag{8}$$

where $\mathbb{E}_{\boldsymbol{h}}\{\cdot\}$ denotes the expectation over the NGV $\boldsymbol{h}$. To satisfy the queue-length bound violation probability constraint given by (5), we require that the effective capacity of the service rate process $R_{\mathrm{p}}(\alpha)$ cannot be smaller than the constant arrival rate $\overline{R}_{\mathrm{A}}$, i.e.,

$$\mathrm{E}_{\mathrm{C}}^{\mathrm{PU}}(\theta,\alpha) \geq T_f B \overline{R}_{\mathrm{A}}. \tag{9}$$

Consequently, PU's statistical delay QoS requirement can be equivalently described by the above *PU's effective capacity constraint*.

IV. Optimal Time-Slot Allocation Scheme

In this section, we obtain the optimal time-slot allocation scheme under our developed framework. Our formulated optimization problem aims at maximizing SU's average throughput subject to the PU's statistical delay QoS requirement given by (9), which can be mathematically written as

$$(\mathrm{P1}) \max_{\alpha(\theta,\boldsymbol{h})} \mathbb{E}_{\boldsymbol{h}}\left\{\frac{(1-\alpha(\theta,\boldsymbol{h}))\,T_f B}{2}\log_2\left(1+\frac{2P_{\mathrm{s}}h_{\mathrm{ss}}}{\sigma^2}\right)\right\} \tag{10}$$

$$\text{s.t. } e^{-\theta T_f B \overline{R}_{\mathrm{A}}} - \mathbb{E}_{\boldsymbol{h}}\left\{e^{-\theta R_{\mathrm{p}}(\alpha(\theta,\boldsymbol{h}))}\right\} \geq 0, \tag{11}$$

$$0 \leq \alpha(\theta,\boldsymbol{h}) \leq 1, \tag{12}$$

where (11) denotes the PU's statistical delay QoS requirement derived by plugging (8) into (9) and $\alpha(\theta,\boldsymbol{h})$ represents the joint time-slot allocation policy which dynamically varies with NGV $\boldsymbol{h}$ and PU's QoS exponent θ. Let $f(\alpha(\theta,\boldsymbol{h})) = -e^{-\theta R_{\mathrm{p}}(\alpha(\theta,\boldsymbol{h}))}$. Then, we have $d^2 f(\alpha(\theta,\boldsymbol{h}))/d\alpha(\theta,\boldsymbol{h})^2 \leq 0$, which implies that $f(\alpha(\theta,\boldsymbol{h}))$ is concave over $\alpha(\theta,\boldsymbol{h})$. As the expectation operation does not change the convexity of $f(\alpha(\theta,\boldsymbol{h}))$ and $e^{-\theta T_f B\overline{R}_{\mathrm{A}}}$ is irrelevant to $\alpha(\theta,\boldsymbol{h})$, PU's effective capacity constraint given by (11) is a concave function of $\alpha(\theta,\boldsymbol{h})$. Moreover, as the objective function given by (10) is a linear and decreasing function of $\alpha(\theta,\boldsymbol{h})$, problem (P1) is concave over $\alpha(\theta,\boldsymbol{h})$ and thus can be solved by the Lagrangian dual method. Construct the Lagrangian function, denoted by $\mathcal{L}(\alpha(\theta,\boldsymbol{h}),\lambda)$, as follows:

$$\mathcal{L}\left(\alpha(\theta,\boldsymbol{h}),\lambda\right) = \mathbb{E}_{\boldsymbol{h}}\left\{g\left(\alpha(\theta,\boldsymbol{h}),\lambda\right)\right\} + \lambda e^{-\theta T_f B\overline{R}_{\mathrm{A}}}, \tag{13}$$

where $g(\alpha(\theta,\boldsymbol{h}),\lambda) = \frac{(1-\alpha(\theta,\boldsymbol{h}))T_f B}{2}\log_2\left(1+\frac{2P_{\mathrm{s}}h_{\mathrm{ss}}}{\sigma^2}\right) - \lambda e^{-\theta R_{\mathrm{p}}(\alpha(\theta,\boldsymbol{h}))}$ and λ is the Lagrangian multiplier associated with PS's effective capacity constraint given by (11). Then, applying the Karush-Kuhn-Tucker (K.K.T.) conditions, the optimal time-slot allocation scheme is determined by

$$\alpha^*_{\mathrm{opt}}(\theta,\boldsymbol{h}) = \min\left\{1, \left[\frac{2\log\left(\frac{\lambda^*\theta(r_{\mathrm{p1}}-r_{\mathrm{p2}})}{r_{\mathrm{s}}}\right) - \theta T_f B r_{\mathrm{p2}}}{\theta T_f B(r_{\mathrm{p1}}-r_{\mathrm{p2}})}\right]^+\right\}, \tag{14}$$

where $r_{\mathrm{p1}} = \log_2\left(1+\frac{2P_{\mathrm{p}}h_{\mathrm{pp}}}{\sigma^2}+\frac{4P_{\mathrm{p}}P_{\mathrm{s}}h_{\mathrm{ps}}h_{\mathrm{sp}}}{\sigma^2+2P_{\mathrm{p}}h_{\mathrm{ps}}+2P_{\mathrm{s}}h_{\mathrm{sp}}}\right)$, $r_{\mathrm{p2}} = \log_2\left(1+\frac{2P_{\mathrm{p}}h_{\mathrm{pp}}}{\sigma^2}\right)$, $r_{\mathrm{s}} = \log_2\left(1+\frac{2P_{\mathrm{s}}h_{\mathrm{ss}}}{\sigma^2}\right)$, $[\cdot]^+$ denotes $\max\{\cdot,0\}$, and λ^* is the optimal Lagrangian multiplier that can be derived by the subgradient method [10].

Remark: We can observe from (14) that our obtained optimal time-slot allocation scheme $\alpha^*_{\mathrm{opt}}(\theta,\boldsymbol{h})$ not only dynamically adjusts according to the NGV $\boldsymbol{h}$, but also varies with PS's statistical delay QoS requirement specified by QoS exponent θ.

V. Fixed Time-Slot Allocation Scheme

We in this section develop a fixed time-slot allocation scheme, where the cooperation time-proportion α does not vary with NGV $\boldsymbol{h}$. Specifically, we also aim at maximizing the CRN's average throughput under PS's statistical delay QoS requirement, which can be mathematically formulated as

$$(\mathrm{P2}) \max_{0\leq\alpha(\theta)\leq 1} \mathbb{E}_{\boldsymbol{h}}\left\{\frac{(1-\alpha(\theta))\,T_f B}{2}\log_2\left(1+\frac{2P_{\mathrm{s}}h_{\mathrm{ss}}}{\sigma^2}\right)\right\} \tag{15}$$

$$\text{s.t. } e^{-\theta T_f B\overline{R}_{\mathrm{A}}} - \mathbb{E}_{\boldsymbol{h}}\left\{e^{-\theta R_{\mathrm{p}}(\alpha(\theta))}\right\} \geq 0, \tag{16}$$

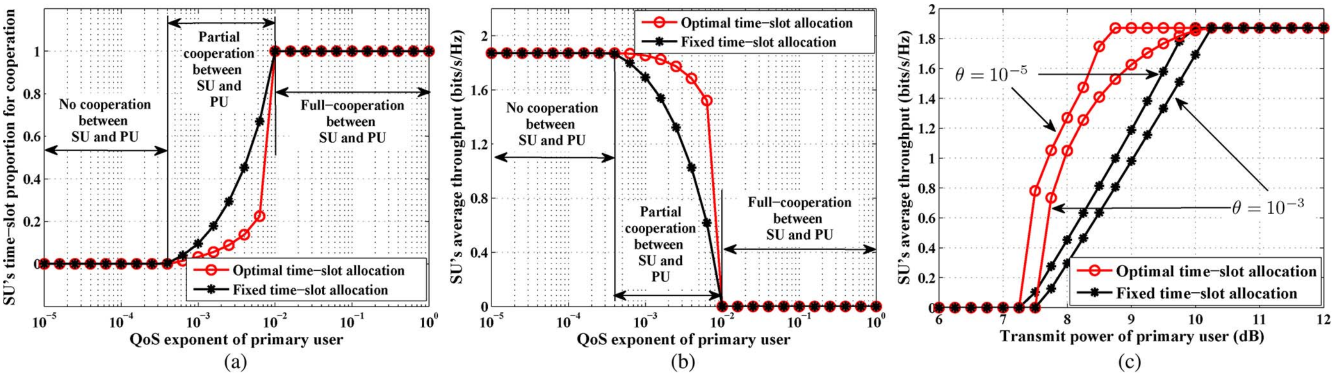
where $\alpha(\theta)$ only varies with PS's QoS exponent θ and PS's data rate $R_{\mathrm{p}}(\alpha(\theta))$ is determined by (1)–(3). Let $t(\alpha(\theta)) = e^{-\theta T_f B\overline{R}_{\mathrm{A}}} - \mathbb{E}_{\boldsymbol{h}}\{e^{-\theta R_{\mathrm{p}}(\alpha(\theta))}\}$, then we can prove that $t(\alpha(\theta))$ monotonically increases with $\alpha(\theta)$. Moreover, we can also prove that the objective function given (15) is a decreasing function of $\alpha(\theta)$. Consequently, the optimal solution, denoted by $\alpha^*_{\mathrm{fixed}}(\theta)$, can be derived as follow.

1) Case 1: If $e^{-\theta T_f B\overline{R}_{\mathrm{A}}} - \mathbb{E}_{\boldsymbol{h}}\{e^{-\theta R_{\mathrm{p}}(\alpha(\theta))}\}|_{\alpha(\theta)=0} \geq 0$ holds, which means that PS's statistical delay QoS constraint can be satisfied even when $\alpha(\theta) = 0$, then the optimal time-allocation scheme to (P2) is $\alpha^*_{\mathrm{fixed}}(\theta) = 0$, which implies that there is *no cooperation* between PN and CRN.

2) Case 2: If $e^{-\theta T_f B\overline{R}_{\mathrm{A}}} - \mathbb{E}_{\boldsymbol{h}}\{e^{-\theta R_{\mathrm{p}}(\alpha(\theta))}\}|_{\alpha(\theta)=1} \leq 0$ holds, i.e., PS's statistical delay QoS requirement cannot be fulfilled even when $\alpha(\theta) = 1$, then the optimal solution is $\alpha^*_{\mathrm{fixed}}(\theta) = 1$. Thus, the CRN goes into *full-cooperation mode*.

3) Case 3: If both $e^{-\theta T_f B\overline{R}_{\mathrm{A}}} - \mathbb{E}_{\boldsymbol{h}}\{e^{-\theta R_{\mathrm{p}}(\alpha(\theta))}\}|_{\alpha(\theta)=0} < 0$ and $e^{-\theta T_f B\overline{R}_{\mathrm{A}}} - \mathbb{E}_{\boldsymbol{h}}\{e^{-\theta R_{\mathrm{p}}(\alpha(\theta))}\}|_{\alpha(\theta)=1} > 0$ hold, then the optimal time-slot allocation $\alpha^*_{\mathrm{fixed}}(\theta)$ is the unique solution to equality $e^{-\theta T_f B\overline{R}_{\mathrm{A}}} - \mathbb{E}_{\boldsymbol{h}}\{e^{-\theta R_{\mathrm{p}}(\alpha(\theta))}\} = 0$, where the closed-form expression does not exist. Thus, the optimal solution can be determined by the bisection method. As the obtained $\alpha^*_{\mathrm{fixed}}(\theta) \in (0,1)$, the CRN is in the *partial-cooperation mode*.

Remark: Comparing with the optimal time-slot allocation scheme $\alpha^*_{\mathrm{opt}}(\theta,\boldsymbol{h})$ in Section IV, our derived fixed time-slot allocation scheme $\alpha^*_{\mathrm{fixed}}(\theta)$ in this section is only determined by the PS's statistical delay QoS requirement specified by the QoS exponent θ, but does not vary with the NGV $\boldsymbol{h}$.



(a) (b) (c)

Fig. 2. Performance evaluation of our proposed optimal and fixed time-slot allocation schemes. (a) SU's average time-slot proportion for cooperation versus PU's QoS exponent. (b) SU's average throughput versus PU's QoS exponent. (c) SU's average throughput versus PU's transmit power.

VI. SIMULATION RESULTS

In this section, we evaluate our proposed optimal and fixed time-slot allocation schemes through simulations. In our simulations, we set the frame duration $T_f = 2$ ms, the bandwidth $B = 10^5$ Hz, the PS's transmit power $P_{\rm p} = 10$ dB, the SS's transmit power $P_{\rm s} = 10$ dB, and the PS's targeted constant-rate arrival process $C_{\rm th} = 185$ Kbits/s.

Fig. 2(a) and (b) show the average time-slot proportion α for PU-SU cooperation and SU's average throughput versus PS's QoS exponent under our proposed optimal and fixed time-slot allocation schemes, respectively. We can observe from these two figures that PS's delay QoS requirement will significantly affect SU's performance. Specifically, when PS's delay QoS requirement is very loose, i.e., the value of PS's QoS exponent θ is small, the average time-slot proportions for both optimal and fixed allocation schemes are zero, which implies that there is *no cooperation* between PU and SU. Thus, SU can achieve the highest throughout. When PS's delay QoS requirement becomes very stringent, i.e., the value of θ is large, the average time-slot proportions for both optimal and fixed allocation schemes equal to 1, which means that SS goes into the *full-cooperation mode*. Therefore, SU in this case gets zero throughput. When PS's delay QoS requirement is neither very loose nor stringent, i.e., the value of θ is neither very small nor large, the average time-slot proportions for both optimal and fixed allocation schemes increase as θ increases, which implies that SU goes into *partial-cooperation mode*. However, in this case, as our proposed optimal time-slot allocation strategy can adapt to the channel conditions, the optimal strategy uses shorter time duration for PU-SU cooperation, implying that the SS-SR pair can obtain longer time duration for their transmission, as compared to the fixed time-slot allocation scheme. Consequently, the optimal strategy achieves higher throughput than the fixed scheme.

In realistic systems, by employing our developed time-slot allocation schemes, SU can dynamically determine the spectrum access approach according to the time-varying types of PU's traffic. In particular, when PU's traffic is non-realtime, SU will not perform cooperation with PU and use half of frame duration for its own transmission. When PU's traffic becomes realtime, SU will give up its own transmission and use up all time resource to help PU meet its targeted delay QoS requirement. When PU's traffic is neither non-realtime nor realtime, SU can adopt the optimal time-slot allocation strategy to maximize its throughput while guaranteeing PU's delay QoS requirement.

Fig. 2(c) shows the SU's average throughput versus the PS's transmit power under our proposed optimal and fixed time-slot allocation schemes. We can observe from Fig. 2(c) that larger PS's transmit power will lead to larger SU's throughput. Moreover, our developed optimal time-slot allocation scheme outperforms the fixed time-slot allocation scheme.

VII. CONCLUSION

In this letter, we proposed a joint time-slot allocation framework for cooperative CRNs with PU's statistical delay QoS protection. Then, we developed the optimal joint time-slot allocation scheme, where the time-slot division adapts to both the channel conditions and PU's delay QoS requirement. Moreover, we investigated a fixed time-slot allocation scheme that only varies with PU's delay QoS requirement. Simulation results showed that the PU's delay QoS requirement will significantly affect the SU's performance.

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