

Chapter 2

Cognitive Point-to-Point Network with Limited Feedback

Abstract In this chapter, we study an opportunistic spectrum sharing scheme in a point-to-point network, where both the primary user and secondary user are power-rate adaptive systems with a few bits of quantized channel feedback from the receivers. The secondary user detects the spectrum opportunities by overhearing the primary feedback and receiving the secondary feedback, and then adapts its power and rate accordingly. The secondary quantization codebook is designed offline by maximizing the secondary average throughput while not causing noticeable degradation to the primary throughput. The secondary quantization and transmission schemes are discussed in three cases when different primary interference information is available at the secondary receiver. Numerical results show that the secondary throughput is greatly improved by the introduction of even 1-bit feedback. Moreover, the secondary throughput increases with more secondary feedback bits or more primary side information.

Keywords Cognitive radio · Spectrum sharing · Quantized channel feedback · Rate loss constraint

2.1 Introduction

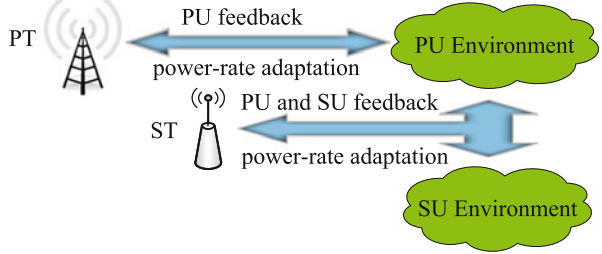
In cognitive radio network, secondary user (SU) aims at detecting and utilizing the spectrum holes of primary user (PU) in a non-intrusive and efficient way. Specifically,

- *PU is oblivious to SU*: PU neither is aware of the existence of SU nor cooperates with SU.
- *SU is non-intrusive to PU*: The interference from SU to PU should not cause a harmful degradation to the PU performance.
- *High spectrum efficiency*: SU achieves good performance.

With these three targets in mind, we study an opportunistic spectrum sharing scheme in the point-to-point network in this chapter [1, 2]. As shown in Fig. 2.1, both the PU

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Fig. 2.1 Spectrum learning and adaptation



and SU are rate adaptive systems with limited channel feedback from the receivers. The primary transmitter (PT) obtains the primary channel information via primary feedback, and then adapts its power and rate accordingly. Since the PU is oblivious to the SU, the primary receiver (PR) neither receives the secondary feedback nor sends cooperative feedback to the SU. The secondary transmitter (ST) detects the spectrum holes non-intrusively, i.e., by eavesdropping the primary channel feedback, and obtains the secondary channel information via the secondary feedback. Then the ST makes efficient spectrum access by adapting its power and rate to the both the primary and secondary feedback. The secondary power and rate are designed not to cause harmful degradation to the average throughput of the PU, which guarantees the non-intrusive spectrum access.

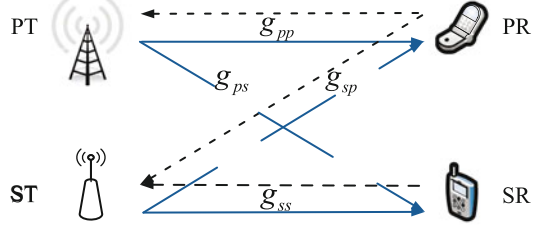
The interference from the PT to secondary receiver (SR) was neglected in previous work [3, 4]. In this work, we consider that the SR may be able to cancel the interference from the PT based on the priori of the primary interference, i.e., primary signal and interference channel. The secondary sharing schemes are discussed in three cases when the SR has full, partial and no priori of the primary interference.

- In Case I, both the primary signal and PT-SR channel are known at the SR;
- In Case II, the primary signal is unknown but PT-SR channel is known at the SR;
- In Case III, neither the primary signal nor PT-SR channel is known at the SR.

Firstly, we propose the quantization, feedback and transmission schemes for the three cases. We establish the primary and secondary quantization codebook with power and rate that are to be obtained in the next step. Secondly, we optimize the power and rate in the primary and secondary quantization codebook offline. The average primary throughput is maximized under the average power constraint of the PU. The average secondary throughput is maximized under the average power constraint of the SU and average rate loss constraint of the PU. Thirdly, we use the optimal quantization codebook online for opportunistic spectrum sharing.

The rest of the chapter is organized as follows. In Sect. 2.2, system model for point-to-point spectrum sharing is introduced. In Sects. 2.3 and 2.4, primary and secondary quantization codebooks are designed, respectively. In Sect. 2.5, numerical results are discussed. Finally, summary is given in Sect. 2.6.

Fig. 2.2 System model of point-to-point spectrum sharing with limited feedback. Signals, interference, primary feedback and secondary feedback are represented by solid, long dashed, dotted, and short dashed arrows, respectively



2.2 System Model

As shown in Fig. 2.2, a pair of ST and SR share the same frequency band with a pair of PT and PR. Denote g_{pp} , g_{ps} , g_{sp} and g_{ss} the instantaneous channel power gains of the PT-PR, PT-SR, ST-PR and ST-SR channels, which follow exponential distribution with mean of $\bar{g}_{pp}$, $\bar{g}_{ps}$, $\bar{g}_{sp}$ and $\bar{g}_{ss}$, respectively. Assume the PT and ST have no information about the instantaneous channels, but know the distributions and mean values of the channel power gains. The PR and SR are assumed to obtain perfect knowledge of g_{pp} and g_{ss} , respectively, through the training process and send a few bits of feedback of the quantized channel power gains to their corresponding transmitters. The additive white Gaussian noise is assumed to be with zero mean and variance N_0 . Consider a block fading scenario where channel remains the same over one block but differs across blocks.

2.3 PU Quantization Codebook

The PT adapts its transmission to the quantized feedback of g_{pp} from the PR. g_{pp} is quantized it into N regions, i.e., $[0, \gamma_1^p)$, $[\gamma_1^p, \gamma_2^p)$, $\dots$, $[\gamma_{N-1}^p, +\infty)$ (let $\gamma_N^p = +\infty$), where γ_n^p ($n = 1, 2, \dots, N-1$) is the boundary of the primary quantization regions. Assume the PR obtains the perfect knowledge of the instantaneous g_{pp} after channel training. If $g_{pp} \in [\gamma_n^p, \gamma_{n+1}^p)$, the PR sends index n back to the PT. The total number of feedback bits for the PU is $\lceil \log_2 N \rceil$. When receiving the primary quantization index n ($n = 0, 1, \dots, N-1$), the PT selects the corresponding power P_n^p and transmission rate R_n^p from the n -th row in the primary quantization codebook as shown in Table 2.1, and uses them in the current block.

Next, we solve the optimal power-rate allocation in Table 2.1. This problem is the same as that in the stand-alone point-to-point network [5, 6] and had also been discussed in [4]. To ensure the non-zero rate in the first quantization region $[0, \gamma_1^p)$, an outage threshold $\gamma_0^p > 0$ is introduced. For each n ($n = 0, 1, \dots, N-1$), the discrete transmission rate is a function of transmit power and quantization threshold, i.e.,

$$R_n^p = \log \left(1 + \frac{\gamma_n^p P_n^p}{N_0} \right). \quad (2.1)$$

Table 2.1 PU quantization codebook for the point-to-point network

g_{pp} region	PU index	PU power and rate
$[0, \gamma_1^p)$	0	P_0^p, R_0^p
$\dots$	$\dots$	$\dots$
$[\gamma_n^p, \gamma_{n+1}^p)$	n	P_n^p, R_n^p
$\dots$	$\dots$	$\dots$
$[\gamma_{N-1}^p, +\infty)$	$N - 1$	P_{N-1}^p, R_{N-1}^p

Note $\log(\cdot)$ stands for natural logarithm function throughout this chapter. Given $\lceil \log_2 N \rceil$ bits of feedback, the optimal γ_n^p and P_n^p ($n = 0, 1, \dots, N - 1$) are obtained by maximizing the average PU throughput $\bar{R}^p$ subject to the average power constraint of the PU P_{th}^p .

$$P2.1 : \max_{\{\gamma_n^p, P_n^p\}} \bar{R}^p = \sum_{n=0}^{N-1} G_n^p R_n^p \quad (2.2)$$

$$\text{s.t. } F^p(\gamma_1^p) P_0^p + \sum_{n=1}^{N-1} G_n^p P_n^p \leq P_{th}^p, \quad (2.3)$$

where $F^p(x) = 1 - \exp(-x/\bar{g}_{pp})$ is the cumulative distribution function (CDF) of g_{pp} , and $G_n^p = F^p(\gamma_{n+1}^p) - F^p(\gamma_n^p) = \exp(-\gamma_n^p/\bar{g}_{pp}) - \exp(-\gamma_{n+1}^p/\bar{g}_{pp})$ is the probability that $g_{pp} \in [\gamma_n^p, \gamma_{n+1}^p)$ for $n = 0, 1, \dots, N - 1$. Problem P2.1 can be solved by Algorithm 1 in [6].

2.4 SU Quantization Codebook

In this section, we discuss the quantization and feedback schemes of the SU and design the optimal power and rate that maximize the average SU throughput.

Assume that the SU has the knowledge of the primary quantization codebook and is able to overhear the primary feedback. To make non-intrusive and efficient spectrum access, the SU adapts its feedback and transmission to the primary environment, i.e., primary channel quality. For each primary index n , the secondary channel power gain is quantized into M regions, i.e., $[0, \gamma_{n,1}^s)$, $[\gamma_{n,1}^s, \gamma_{n,2}^s)$, $\dots$, $[\gamma_{n,(M-1)}^s, +\infty)$ (let $\gamma_{n,M}^s = +\infty$), where $\gamma_{n,m}^s$ ($m = 1, 2, \dots, M - 1$) indicates the secondary quantization threshold. When the secondary channel power gain falls into a certain region, i.e., $[\gamma_{n,m}^s, \gamma_{n,(m+1)}^s)$, index m is sent from the SR to the ST. The total number of feedback bits for the SU is $\lceil \log_2 M \rceil$. When the ST receives the secondary index m ($m = 0, 1, \dots, M - 1$) and overhears the primary index n , it selects the corresponding power $P_{n,m}^s$ and rate $R_{n,m}^s$ from the n -th row and m -th column in the secondary quantization codebook as shown in Table 2.2, and uses them to the end of the current block. As mentioned, both the primary and secondary quantization codebooks are designed offline.

Table 2.2 SU quantization codebook for the point-to-point network

PU index	SU index				
	0	...	m	...	$M - 1$
0	$[0, \gamma_{0,1}^s)$ $P_{0,0}^s$ $R_{0,0}^s$	...	$[\gamma_{0,m}^s, \gamma_{0,(m+1)}^s)$ $P_{0,m}^s$ $R_{0,m}^s$	...	$[\gamma_{0,(M-1)}^s, +\infty)$ $P_{0,(M-1)}^s$ $R_{0,(M-1)}^s$
...	...	...	...	...	...
n	$[0, \gamma_{n,1}^s)$ $P_{n,0}^s$ $R_{n,0}^s$	...	$[\gamma_{n,m}^s, \gamma_{n,(m+1)}^s)$ $P_{n,m}^s$ $R_{n,m}^s$	...	$[\gamma_{n,(M-1)}^s, +\infty)$ $P_{n,(M-1)}^s$ $R_{n,(M-1)}^s$
...	...	...	...	...	...
$N - 1$	$[0, \gamma_{(N-1),1}^s)$ $P_{(N-1),0}^s$ $R_{(N-1),0}^s$	...	$[\gamma_{(N-1),m}^s, \gamma_{(N-1),(m+1)}^s)$ $P_{(N-1),m}^s$ $R_{(N-1),m}^s$	...	$[\gamma_{(N-1),(M-1)}^s, +\infty)$ $P_{(N-1),(M-1)}^s$ $R_{(N-1),(M-1)}^s$

Define the relative degradation of the primary throughput due to the existence of the SU as the primary rate loss ratio, i.e.,

$$p_{RL}^p = 1 - \underline{R}^p / \bar{R}^p, \quad (2.4)$$

where $\underline{R}^p$ and $\bar{R}^p$ are the average PU throughput with and without the existence of the SU, respectively. $\bar{R}^p$ was given in (2.2) and $\underline{R}^p$ will be derived in Sects. 2.4.1, 2.4.2 and 2.4.3 for the three cases. To protect the average throughput of the PU, the primary rate loss ratio is constrained within the rate loss constraint (RLC), i.e., $p_{RL}^p \leq r_{RL}^p$. It was claimed in [7] that RLC outperforms that of the instantaneous interference constraint in terms of spectrum utilization efficiency.

Next, we design the optimal secondary quantization thresholds $\gamma_{n,m}^s$ and transmit power $P_{n,m}^s$ ($n = 0, 1, 2, \dots, N - 1$ and $m = 0, 1, 2, \dots, M - 1$) in Table 2.2 by maximizing the average secondary throughput $\bar{R}^s$ subject to the primary RLC r_{RL}^p and the average secondary power constraint P_{th}^s .

$$P2.2 : \max_{\{\gamma_{n,m}^s, P_{n,m}^s\}} \bar{R}^s \quad (2.5)$$

$$\text{s.t. } p_{RL}^p \leq r_{RL}^p \quad (2.6)$$

$$\bar{P}^s \leq P_{th}^s, \quad (2.7)$$

where $\bar{P}^s$ is the average secondary transmit power.

Since the PU is oblivious to the SU, it does not control its interference to the SU. However, the SR may cancel the interference from the PT based on the availability of the primary signal and interference channel gain g_{ps} . In the following discussions, the secondary quantization codebook design are discussed in three cases in terms of the priori information of the primary interference. In Case I, both the primary signal

and g_{ps} are known at the SR. In Case II, the primary signal is unknown but g_{ps} is known at the SR. In Case III, neither the primary signal nor g_{ps} is known at the SR. For each case, $\bar{R}^s$, $\bar{P}^s$ and $\underline{P}_{RL}^p$ in P2.2 will be derived.

2.4.1 Case I: Full Priori of PU Interference

In this case, both the primary signal and g_{ps} are known at the SR. The interference from the PU to SU can be fully canceled. The secondary quantization thresholds are based on g_{ss} only. g_{ss} is quantized into M regions, i.e., $[0, \gamma_1^s)$, $[\gamma_1^s, \gamma_2^s)$, $\dots$, $[\gamma_{M-1}^s, \infty)$, where γ_m^s ($m = 1, 2, \dots, M-1$) indicate the quantization boundaries. Since the secondary quantization is not related to the PU, we have $\gamma_{1,m}^s = \gamma_{2,m}^s = \dots = \gamma_{(N-1),m}^s = \gamma_m^s$ for each secondary index m in Table 2.2. When the ST overhears the primary index n and receives secondary index m , it selects power $P_{n,m}^s$ and transmission rate $R_{n,m}^s$ from the secondary quantization codebook until the end of current block, where $R_{n,m}^s = \log(1 + P_{n,m}^s \gamma_m^s / N_0)$ for $n = 0, 1, \dots, N-1$ and $m = 0, 1, \dots, M-1$. An outage threshold $\gamma_0^s > 0$ is introduced to guarantee the non-zero rate in $[0, \gamma_1^s)$. In the following discussions, we derive $\bar{R}^s$, $\bar{P}^s$ and $\underline{R}^p$ in P2.2.

2.4.1.1 Average SU Throughput

Define the CDF of g_{ss} by $F^s(x) = 1 - \exp(-x/\bar{g}_{ss})$. $G_m^s = F^s(\gamma_{m+1}^s) - F^s(\gamma_m^s)$ is the probability that $g_{ss} \in [\gamma_m^s, \gamma_{m+1}^s)$. The secondary transmission is successful if the secondary channel capacity $C_{n,m}^s = \log(1 + P_{n,m}^s g_{ss} / N_0)$ exceeds the target rate $R_{n,m}^s$, which implies $g_{ss} \geq \gamma_m^s$. Thus, G_m^s is the joint probability of the event that the ST transmits with $R_{n,m}^s$ and the event that the transmission is successful. As discussed, $F^p(\gamma_1^p)$ is the probability that $g_{pp} \in [0, \gamma_1^p)$ and $G_n^p = F^p(\gamma_{n+1}^p) - F^p(\gamma_n^p)$ is the probability that $g_{pp} \in [\gamma_n^p, \gamma_{n+1}^p)$. Given primary index 0 and secondary index m , the achievable secondary rate is $F^p(\gamma_1^p) G_m^s R_{0,m}^s$. Given primary index n and secondary index m , the achievable secondary rate is $G_n^p G_m^s R_{n,m}^s$. Considering all N PU index and M SU index in Table 2.2, the average SU throughput is given by

$$\bar{R}^s = F^p(\gamma_1^p) \left[\sum_{m=0}^{M-1} G_m^s R_{0,m}^s \right] + \sum_{n=1}^{N-1} G_n^p \left[\sum_{m=0}^{M-1} G_m^s R_{n,m}^s \right]. \quad (2.8)$$

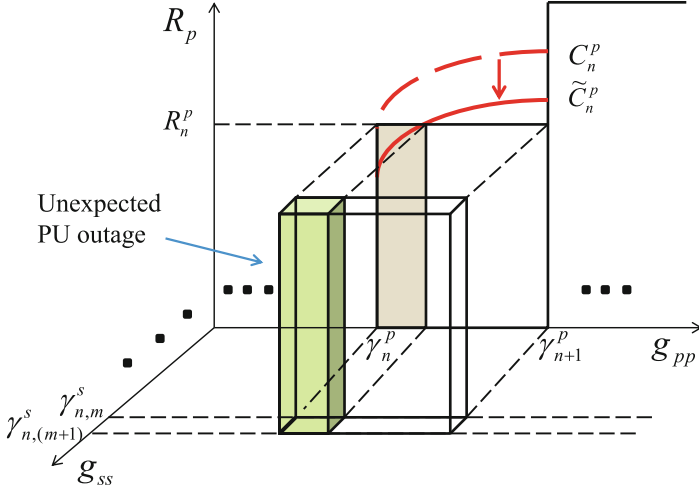


Fig. 2.3 Primary rate loss due to the existence of SU

2.4.1.2 Average SU Power

The average transmit power of the SU is given by

$$\bar{P}^s = F^p(\gamma_1^p) \left[F^s(\gamma_1^s) P_{0,0}^s + \sum_{m=1}^{M-1} G_m^s P_{0,m}^s \right] + \sum_{n=1}^{N-1} G_n^p \left[F^s(\gamma_1^s) P_{n,0}^s + \sum_{m=1}^{M-1} G_m^s P_{n,m}^s \right]. \quad (2.9)$$

2.4.1.3 PU Rate Loss Ratio

As discussed, $\bar{R}^p$ was given in (2.2). To obtain p_{RL}^p , $\underline{R}^p$ is derived. If $g_{pp} \in [\gamma_n^p, \gamma_{n+1}^p)$, the PT transmits with the power P_n^p and transmission rate R_n^p , where $R_n^p = \log(1 + P_n^p \gamma_n^p / N_0)$.

- In the absence of the SU, the primary channel capacity is given by $C_n^p = \log(1 + P_n^p g_{pp} / N_0)$. The primary transmission is always successful ($C_n^p \geq R_n^p$) since $g_{pp} \geq \gamma_n^p$.
- In the presence of the SU, the primary channel capacity is given by $\tilde{C}_n^p = \log(1 + P_n^p \tilde{g}_{pp} / N_0)$, where $\tilde{g}_{pp} = \frac{\tilde{g}_{pp}}{1 + g_{sp} P_{n,m}^s / N_0}$ is the effective channel gain of the primary channel. The primary transmission is successful ($\tilde{C}_n^p \geq R_n^p$) if $\tilde{g}_{pp} \geq \gamma_n^p$. Otherwise, outage occurs. An example of the primary outage event given a pair of P_n^p and $P_{n,m}^s$ is shown in the shaded cuboid of Fig. 2.3.

Therefore, at the presence of the SU, the average primary throughput is given by

$$\begin{aligned} \underline{R}^p = & \sum_{n=0}^{N-1} R_n^p \left\{ \Pr(\tilde{g}_{pp} \geq \gamma_n^p, \gamma_n^p \leq g_{pp} < \gamma_{n+1}^p) F^s(\gamma_1^s) \right. \\ & \left. + \sum_{m=1}^{M-1} \Pr(\tilde{g}_{pp} \geq \gamma_n^p, \gamma_n^p \leq g_{pp} < \gamma_{n+1}^p) G_m^s \right\}, \end{aligned} \quad (2.10)$$

which is further derived as

$$\begin{aligned} \underline{R}^p = & \sum_{n=0}^{N-1} R_n^p \left\{ \left[e^{-\frac{\gamma_n^p}{\tilde{g}_{pp}}} - e^{-\frac{\gamma_{n+1}^p}{\tilde{g}_{pp}}} + \frac{1}{1 + \frac{\tilde{g}_{pp} N_0}{\gamma_n^p \tilde{g}_{sp} P_{n,0}^s}} \right. \right. \\ & \times \left. \left(e^{-\frac{\gamma_{n+1}^p}{\tilde{g}_{pp}} + \frac{N_0}{\tilde{g}_{sp} P_{n,0}^s} \left(1 - \frac{\gamma_{n+1}^p}{\gamma_n^p}\right)} - e^{-\frac{\gamma_n^p}{\tilde{g}_{pp}}} \right) \right] F^s(\gamma_1^s) \\ & + \sum_{m=1}^{M-1} \left[e^{-\frac{\gamma_n^p}{\tilde{g}_{pp}}} - e^{-\frac{\gamma_{n+1}^p}{\tilde{g}_{pp}}} + \frac{1}{1 + \frac{\tilde{g}_{pp} N_0}{\gamma_n^p \tilde{g}_{sp} P_{n,m}^s}} \right. \\ & \times \left. \left. \left(e^{-\frac{\gamma_{n+1}^p}{\tilde{g}_{pp}} + \frac{N_0}{\tilde{g}_{sp} P_{n,m}^s} \left(1 - \frac{\gamma_{n+1}^p}{\gamma_n^p}\right)} - e^{-\frac{\gamma_n^p}{\tilde{g}_{pp}}} \right) \right] G_m^s \right\}. \end{aligned} \quad (2.11)$$

$\underline{R}^p$ is related to the average channel statistics instead of the instantaneous channel power gains. Substituting (2.11) into (2.4), we obtain the primary rate loss ratio.

2.4.2 Case II: Partial Priori of PU Interference

In this case, g_{ps} is available at the SR while the primary signal is not. The primary interference is treated as noise. Given the primary index n , the SR can deduce the primary transmit power P_n^p from the primary quantization codebook and then calculate the effective channel power gain $\tilde{g}_{ss} = \frac{g_{ss}}{1 + g_{ps} P_n^p / N_0}$ for the secondary channel. Different from Case I where the quantization of g_{ss} is regardless of the primary feedback, in this case, the quantization of the $\tilde{g}_{ss}$ is related to n . For each index n ($n = 0, 1, \dots, N-1$), $\tilde{g}_{ss}$ is quantized into M regions, i.e., $[0, \gamma_{n,1}^s), [\gamma_{n,1}^s, \gamma_{n,2}^s), \dots, [\gamma_{n,(M-1)}^s, +\infty)$, where $\gamma_{n,m}^s$ ($m = 1, 2, \dots, M-1$) is the secondary quantization threshold. If $\tilde{g}_{ss} \in [\gamma_{n,m}^s, \gamma_{n,(m+1)}^s)$, the SR feeds back index m to the ST. Then, the ST selects power $P_{n,m}^s$ and rate $R_{n,m}^s = \log(1 + P_{n,m}^s \gamma_{n,m}^s / N_0)$ from Table 2.2 for $n = 0, 1, \dots, N-1$ and $m = 0, 1, \dots, M-1$. The outage thresholds $\gamma_{n,0}^s > 0$ is introduced to guarantee the non-zero rate in $[0, \gamma_{n,1}^s)$. The CDF of $\tilde{g}_{ss}$ is given by

$$\tilde{F}^s(x) = 1 - \frac{\tilde{g}_{ss} N_0}{\tilde{g}_{ss} N_0 + P_n^p \tilde{g}_{ps} x} \exp\left(-\frac{x}{\tilde{g}_{ss}}\right). \quad (2.12)$$

The probabilities of $\tilde{g}_{ss} \in [\gamma_{n,m}^s, \gamma_{n,(m+1)}^s)$ is represented as $\tilde{G}_{n,m}^s = \tilde{F}^s(\gamma_{n,(m+1)}^s) - \tilde{F}^s(\gamma_{n,m}^s)$.

2.4.2.1 Average SU Throughput

The average secondary throughput is given by

$$\bar{R}^s = F^p(\gamma_1^p) \sum_{m=0}^{M-1} \tilde{G}_{0,m}^s R_{0,m}^s + \sum_{n=1}^{N-1} G_n^p \left[\sum_{m=0}^{M-1} \tilde{G}_{n,m}^s R_{n,m}^s \right]. \quad (2.13)$$

2.4.2.2 Average SU Power

The average transmit power of SU is given by

$$\begin{aligned} \bar{P}^s = F^p(\gamma_1^p) & \left[\tilde{F}^s(\gamma_{0,1}^s) P_{0,0}^s + \sum_{m=1}^{M-1} \tilde{G}_{0,m}^s P_{0,m}^s \right] \\ & + \sum_{n=1}^{N-1} G_n^p \left[\tilde{F}^s(\gamma_{n,1}^s) P_{n,0}^s + \sum_{m=1}^{M-1} \tilde{G}_{n,m}^s P_{n,m}^s \right]. \end{aligned} \quad (2.14)$$

2.4.2.3 PU Rate Loss Ratio

Similar to the discussions in Case I, the average PU rate at the presence of SU is given by

$$\begin{aligned} \underline{R}^p = \sum_{n=0}^{N-1} R_n^p & \left\{ \Pr(\tilde{g}_{pp} \geq \gamma_n^p, \gamma_n^p \leq g_{pp} < \gamma_{n+1}^p) \tilde{F}^s(\gamma_{n,1}^s) \right. \\ & \left. + \sum_{m=1}^{M-1} \Pr(\tilde{g}_{pp} \geq \gamma_n^p, \gamma_n^p \leq g_{pp} < \gamma_{n+1}^p) \tilde{G}_{n,m}^s \right\}. \end{aligned} \quad (2.15)$$

Substituting (2.15) into (2.4), we obtain the primary rate loss ratio.

2.4.3 Case III: No Prior of PU Interference

In this case, neither the primary signal nor g_{ps} is known at the SR. The primary signal is also treated as noise as in Case II. Due to the lack of g_{ps} , the SU is not able to quantize the secondary channel based on $\tilde{g}_{ss}$. Conservatively, we adopt the same method as in Case I by quantizing g_{ss} into M regions, i.e., $[0, \gamma_1^s)$, $[\gamma_1^s, \gamma_2^s)$, $\dots$, $[\gamma_{M-1}^s, +\infty)$. Similar to Case I, we also have $\gamma_{1,m}^s = \gamma_{2,m}^s = \dots = \gamma_{(N-1),m}^s = \gamma_m^s$ for each secondary index m in Table 2.2.

The secondary channel capacity and transmission rate are denoted by $C_{n,m}^s = \log(1 + P_{n,m}^s \tilde{g}_{ss}/N_0)$ and $R_{n,m}^s = \log(1 + P_{n,m}^s \gamma_m^s/N_0)$ for $n = 0, 1, \dots, N-1$ and $m = 0, 1, \dots, M-1$. Given a secondary index m , the transmission is successful if $C_{n,m}^s \geq R_{n,m}^s$. Then, the joint probability that the ST transmits with $R_{n,m}^s$ and the transmission is successful is $\Pr(\tilde{g}_{ss} \geq \gamma_m^s, \gamma_m^s \leq g_{ss} < \gamma_{m+1}^s)$. Therefore, the average secondary rate is given by

$$\begin{aligned} \bar{R}^s = & F^p(\gamma_1^p) \sum_{m=0}^{M-1} [\Pr(\tilde{g}_{ss} \geq \gamma_m^s, \gamma_m^s \leq g_{ss} < \gamma_{m+1}^s) R_{0,m}^s] \\ & + \sum_{n=1}^{N-1} \left\{ G_n^p \sum_{m=0}^{M-1} [\Pr(\tilde{g}_{ss} \geq \gamma_m^s, \gamma_m^s \leq g_{ss} < \gamma_{m+1}^s) R_{n,m}^s] \right\}. \end{aligned} \quad (2.16)$$

Since the quantization region is based on g_{ss} , then $\bar{P}_s$ and $\bar{R}^p$ are regardless of the primary interference and are given by (2.9) and (2.11), respectively, as in Case I.

2.5 Numerical Results

Substituting $\bar{R}_s$, $\bar{P}_s$ and $\bar{R}^p$ for the three cases into P2.2, it is seen that P2.2 is a non-linear, non-convex and multi-modal problem which cannot be solved by most of the derivative-based optimization methods. To find the global optimal solution, Differential Evolution [8, 9], a multiple starting point, derivative-free global optimization method, is adopted with the constrained handling technique [10]. Once the global optimal secondary thresholds $\gamma_{n,m}^s$ and power $P_{n,m}^s$ in secondary quantization codebook are determined, they can be used in the online transmissions.

In this section, the numerical results for the average throughput of PU and the SU are presented. We set $\bar{g}_{pp} = 1$, $\bar{g}_{sp} = 0.5$, $\bar{g}_{ps} = 0.5$, $\bar{g}_{ss} = 4$ and $N_0 = 1$ throughout this section.

In Fig. 2.4, at the absence of the SU, the average primary throughput $\bar{R}^p$ increases as the increase of the number of primary feedback bits. The primary throughput with a few bits of feedback is almost as good as that of having perfect CQI at the PT. Moreover, $\bar{R}^p$ improves for higher primary power constraint P_{th}^p .

In the following discussions, we fix the primary power constraint $P_{th}^p = 10$ dB and the primary RLC $r_{RL}^p = 0.1$ which represents that the maximum throughput loss

Opportunistic Spectrum Sharing in Cognitive Radio
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