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A Cooperation and Access Spectrum Sharing Protocol with Cooperative Interference Management

Ping Xie · Lihua Li · Junlong Zhu · Ruijuan Zheng · Mingchuan Zhang

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Abstract In cognitive radio network, the spectrum sharing is considered where secondary (unlicensed) users' communication co-exists with primary (licensed) users' communication in the presence of an interferer, and the interferer has a significant impact on the primary performance. Hybrid ARQ (automatic-repeat-request) retransmission mechanisms are employed at primary and interfering links. Based on the mechanisms, a cooperate-and-access spectrum sharing protocol is proposed where the secondary system switches between cooperation mode with forwarding interference and access mode with decoding interfering packet. In the cooperation mode, the secondary transmitter forwards information about the interference to the primary receiver for interference mitigation. Thus, the primary performance is improved compared to the traditional non-cooperative communication system and credits are collected by the secondary system. Adequate credits allow the secondary system running on the access mode, i.e. the secondary packet is delivered to the secondary receiver by using the primary spectrum. Then, compared to the traditional system the primary performance is degraded in the access mode. The condition that this degradation can be fully offset by the advantage accrued from interference mitigation is investigated. The primary throughput in cooperation and access modes and the secondary throughput in access mode are derived. Numerical results show that the proposed protocol has the equal or higher average primary throughput than the traditional system in the low primary SNR region. In addition, when the average transmits SNR of the primary is less than that of the interfering user, the proposed protocol is more efficient than the protocol in Li et al. (IEEE Transactions on Communication 60(10):2861–2870, 2012).

Keywords Cognitive radio · Interference forwarding · Cooperation spectrum sharing · Credits · Hybrid ARQ

P. Xie (✉) · R. Zheng · M. Zhang
Information Engineering College, Henan University of Science and Technology, Luoyang 471023, China
e-mail: xieping_1984@bupt.edu.cn

L. Li · J. Zhu
The State Key Laboratory of Networking and Switching Technology, Beijing University of Posts and Telecommunication, No.10, Xitucheng Road, Haidian District, Beijing, China

1 Introduction

With the development of wireless communication and the steadily increasing demands for higher quality of service (QoS), the spectrum scarcity problem has become increasingly serious. The low utilization efficiency of the radio spectrum is the critical factor that leads to this problem. Cognitive radio (CR) [1] has been recently proposed, which is a promising technology for improving the utilization efficiency of radio spectrum [2]. The main idea of this technology is to allow secondary user (SU) networks to coexist with primary user (PU) networks through spectrum sharing, provided that the secondary spectrum access will not adversely affect the performance of PU. Based on the type of available network side information along with the regulatory constraints, there are three CR network models [3]: interweave, underlay, and overlay. Overlay model is a special dynamic spectrum-sharing model that allows the SUs to simultaneously transmit with the PUs over the same spectrum, provided that the SUs aid the PUs transmission by cooperative communication techniques such as the advanced coding techniques and cooperative-relaying techniques. The overlay model has attracted considerable research interest [4–8], when spectrum-sharing protocols based on cooperative amplify-and-forward (AF) were proposed in Refs. [4,5] and the protocol based on decode-and-forward (DF) was proposed in Ref. [6]. In [7–9], the DF-based spectrum-sharing protocols were generalized for a multi-user scenario, in which some methods were adopted in selecting the relay. A cooperate-and-access spectrum-sharing protocol in Ref. [12] is proposed where the secondary system alternates between cooperation and access modes.

The research in [4–9] and [12] all assume that secondary users act as a relay to assist the primary transmission, where the cooperation approach between PUs and SUs can be referred as conventional cooperation approach. Recently, another cooperative methodology is investigated, in which SUs can decode the interferer packet and forward it to the primary nodes. The latter approach can be referred as cooperative interference management (CIM). From an information-theoretic standpoint, the researches in Refs. [10,11] have indicated that the CIM is superior to the conventional cooperation approach in interference-limited scenarios. But the research on CIM of [10,11] focused on relay networks without spectrum sharing along with static and known channels. The probability that SUs access to the primary spectrum is investigated in Ref. [13], where the primary performance is enhanced via interference mitigation. The outage probabilities of the primary link and secondary link are obtained by the maximum rate achievable in multiple access channel (MAC), the Eq. (12) of [13] is very complex, and how much the value of α can be fixed is not illustrated.

Based on the research in [11,12], a cooperate-and-access spectrum sharing protocol is investigated where the secondary system switches between cooperation mode with forwarding interference and access mode with decoding interfering packet in this paper. In interference-limited scenarios, the protocol of Ref. [12] may be invalid. Thus, in the proposed protocol credits are collected by forwarding interference rather than relaying the primary packet. The operation mode of the secondary system is also divided into cooperation and access modes, and each mode is described in this paper. The main contributions of this work are as follows: (1) A cooperate-and-access spectrum sharing protocol is proposed where the secondary system switches between cooperation mode with forwarding interference and access mode with decoding the interfering signal. (2) The ARQ transport mechanisms in cooperation and access modes are designed. (3) The primary throughput in cooperation and access modes are derived. The secondary throughput in access mode is derived. Credits and penalties which are characterized by primary throughput are also derived. And the minimum times of secondary system running on the cooperation mode is discussed. (4) The com-

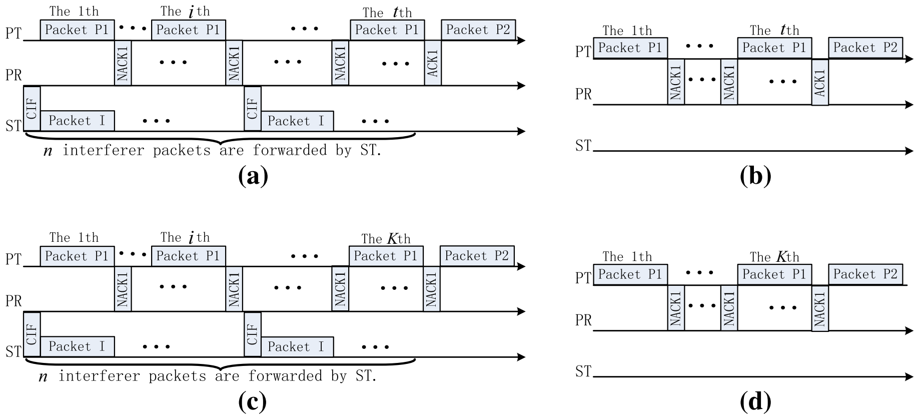

Fig. 1 The ARQ mechanisms in cooperation mode with forwarding interference. **a** An illustration of event $\{\mathcal{C}_{\mathcal{I}}, \mathcal{C}_{\mathcal{I}r}\}$. **b** An illustration of event $\{\mathcal{C}_{\mathcal{I}}, \overline{\mathcal{C}}_{\mathcal{I}r}\}$. **c** An illustration of event $\{\mathcal{C}_{\mathcal{I}\mathcal{L}}, \mathcal{C}_{\mathcal{I}r}\}$. **d** An illustration of event $\{\mathcal{C}_{\mathcal{I}\mathcal{L}}, \overline{\mathcal{C}}_{\mathcal{I}r}\}$

parison of the proposed protocol, the protocol in Ref. [12], and traditional non-cooperative communication system (referred to as traditional primary system) is revealed in the simulation results. The results show that the proposed protocol and the protocol in Ref. [12] may bring about greater system performance not only for the primary system but also for the secondary system than the traditional primary communication system in the low primary SNR region. And if the average transmit SNR of the primary is less than that of the interferer, the proposed protocol has the best performance, otherwise the protocol in Ref. [12] has the best performance. In the high primary SNR region, the primary performances in those three protocols are basically the same. The rest of the paper is organized as follows. Section 2 depicts communication model. Section 3 deduces the throughput of the primary and secondary. Section 4 analyzes the credits and penalties. Numerical results are provided in Sect. 5 to compare performance of the proposed protocol, the protocol in Ref. [12], and the traditional primary communication system with no spectrum sharing. Finally, conclusions are drawn in Sect. 6.

2 The Description of Communication Model

2.1 System Model

The system model is shown as Fig. 1 in [13]. A primary link, a secondary link and an interfering link are arranged in this system model, and each link contains a source and a destination. Because of the interferer, primary and secondary systems may suffer poor performance. An application scenario is elaborated in [13], which considers that primary receiver (PR) and secondary receiver (ST) are a picocell base station and a neighboring femtocell base station respectively, and interfering transmitter (IT) is a macrocell base station which encompasses the femtocell and the picocell. Primary transmitter (PT) and secondary transmitter (ST) are a picocell user and a femtocell user respectively, and interfering receiver (IR) is a macrocell user. In this case, the disturbance caused by the interference becomes the main bottleneck in the performance of the PT-PR link.

The main idea of the spectrum sharing protocol in this paper can be illustrated as follows. The secondary system is run on cooperation mode at first, at this point, ST is always willing to decode the interfering packet and forward it to the primary nodes. Interfering packet forwarding can promote the reception of the interference at PR. Then PR can decode the interfering signal jointly with the useful signal. Thus, the primary performance is improved by interference mitigation compared to the traditional primary system, and credits are accumulated by the secondary system. Since credits are collected enough, secondary packets are allowed to be delivered by using the primary spectrum. This phenomenon indicates that the operation mode of the secondary system is changed into access mode, where the primary throughput is degraded because of the transmission of the secondary packet. In the overlay model of cognitive radio, it must to ensure that the system performance of the primary is not worse than the traditional primary system. Thus, the degradation must be fully offset by credits. In other words, the secondary system must spend enough times running on cooperation mode for accumulating credits. As credits declined to zero, the secondary system must switch back to cooperation mode to accumulate new credits. Cooperation and access modes are executed circularly. In the effective protocol, credits accumulated in cooperation mode must be sufficient to compensate for the degradation of primary throughput in access mode. The secondary system is assumed to be no delay-limited, and thus latency is not an issue. This is typical for example in wireless sensor networks [14] where the sensors send non-time-critical data back to the controller. The transport mechanisms in cooperation and access modes are explained in detail in Sects. 2.3 and 2.4 respectively.

The channels over links PT $\rightarrow$ PR, PT $\rightarrow$ ST, ST $\rightarrow$ SR, IT $\rightarrow$ PR, IT $\rightarrow$ ST, ST $\rightarrow$ PR, IT $\rightarrow$ SR and PT $\rightarrow$ SR are modeled to be Rayleigh flat fading with channel coefficients denoted by h_P, h_{PS}, h_S, h_{IP}, h_{IS}, h_{SP}, h_{ISR} and h_{PSR}, respectively. Those channel coefficients are independent complex Gaussian random variables with zero mean and unit power. A wireless channel link i can be characterized by a small-scale fading coefficient and a path loss $d_i^{-\alpha}$. Where d_i indicates the length of link i, and α is the path loss exponent. It is supposed that all channel coefficients remain static during each transmission slot, but change independently from slot to slot. No Channel State Information (CSI) is assumed at the primary transmitter, but full CSI is available at the receivers and the secondary transmitter. The primary, secondary and interfering transmission rates are denoted by R_P, R_S and R_I respectively. P_P, P_S and P_I are the transmit powers of PT, ST and IT respectively. The codebook used by the interferer is assumed to be known at PR, ST and SR.

In a system with type-I HARQ, if a packet is successfully received by the receiver, a control message i.e. ACK (acknowledgement) from the receiver will be sent back to the transmitter. When the transmitter received an ACK, it deems that a packet is successfully delivered to the receiver; when the transmitter received a NACK (No Acknowledgement) or did not receive any feedback signal, it deems that a packet is not successfully delivered to the receiver, and the transmitter will retransmit the packet until an ACK is received by the transmitter or the times of retransmission reach to the maximum. The maximum times of retransmission is predetermined by the system. At the last retransmission, if the transmitter still does not receive an ACK, it denotes that a packet is lost, and then a new packet will be transmitted in the next time slot. In this paper, type-I HARQ is employed in both links PT $\rightarrow$ PR and IT $\rightarrow$ IR, and each packet can be transmitted at most K times in the primary system and K_I times in the interfering system, where $K \geq 2$, $K_I \geq 2$. And it is assumed that ST always has a packet to transmit to SR and a best-effort mechanism is adopted where each packet is transmitted only once. Type-I HARQ is selected for simplicity of analysis, but the proposed principle can also be applied to more complex forms of HARQ.

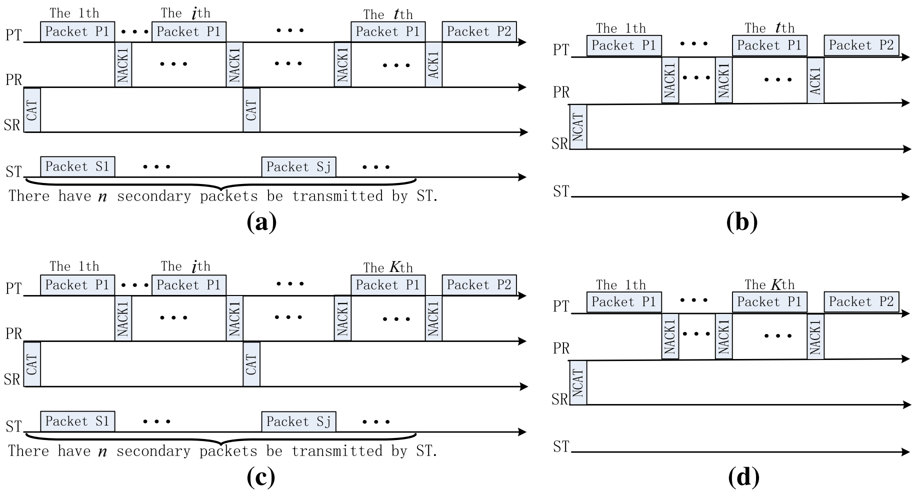

Fig. 2 The ARQ mechanisms in the access mode with decoded the interfering signal. **a** An illustration of event $\{\mathcal{A}_{\mathcal{I}}, \mathcal{A}_{\mathcal{I}r}\}$. **b** An illustration of event $\{\mathcal{A}_{\mathcal{I}}, \bar{\mathcal{A}}_{\mathcal{I}r}\}$. **c** An illustration of event $\{\mathcal{A}_{\mathcal{I}\mathcal{L}}, \mathcal{A}_{\mathcal{I}r}\}$. **d** An illustration of event $\{\mathcal{A}_{\mathcal{I}\mathcal{L}}, \bar{\mathcal{A}}_{\mathcal{I}r}\}$

2.2 Traditional Primary System

In traditional non-cooperative communication system (regarded as traditional primary system), secondary users are not considered, but several interferences may be coexisting. In this paper, an interferer is introduced to the system model. The ARQ (an automatic repeat-request) mechanisms in conventional primary system of [12] are adopted in this subsection. An example of the idea is shown in Fig. 2 of Ref. [12]. Due to the presence of the interferer, the received signal at PR in traditional primary system can be written as

$$y_P(t) = \sqrt{P_P d_P^{-\alpha}} h_P(t) x_P(t) + \sqrt{P_I d_{IP}^{-\alpha}} h_{IP}(t) x_I(t) + n(t), \tag{1}$$

where $x_P(t)$ and $x_I(t)$ are the transmitted signal symbol from PT and IT respectively, with $E\left[|x_P(t)|^2\right] = 1$ and $E\left[|x_I(t)|^2\right] = 1$. $E[X]$ represents the mean of X. $n(t)$ is the receiver noise at PR, which is the complex white Gaussian noise with zero mean and power N. Thus in a time slot, the outage probability of the primary in this mode can be written as

$$O_P = \Pr\left\{\frac{P_P d_P^{-\alpha} |h_P(t)|^2}{P_I d_{IP}^{-\alpha} |h_{IP}(t)|^2 + N} < \rho_P\right\} = 1 - \frac{P_P d_P^{-\alpha} \exp(-\rho_P N/(P_P d_P^{-\alpha}))}{\rho_P P_I d_{IP}^{-\alpha} + P_P d_P^{-\alpha}}, \tag{2}$$

where $\rho_P = 2^{R_P} - 1$.

2.3 Cooperation Mode with Forwarding Interference

In cooperation mode with forwarding interference, ST constantly monitors the interfering packets and the ACK/NACK feedbacks. The signal from IT is always willing to be decoded by ST. In one time slot, event ξ is defined as the state that the interfering signal is decoded successfully by ST, and the complementary event is defined as $\overline{\xi}$. Event ζ is defined as the state that the transmission times of an interfering packet is not reach to the maximum. And event ς is defined as the state that ST receives a NACK or no feedback signal from IT. ST can not to forward the interfering signal to PR in the next slot only as the events ξ, ζ and ς all occur in the current time slot. If ST can forward the interfering signal to PR that is defined as the event $\mathcal{F}$, $\mathcal{F} = \xi \cap \zeta \cap \varsigma$, ST is to broadcast a Cooperative-Interference-Forward (CIF) message. Otherwise ST stays silent which is defined as the event $\overline{\mathcal{C}}_{\mathcal{I}r}$. And event $\mathcal{F}_i$ represents that the event $\mathcal{F}$ occurs at the i-th retransmission slot of the primary packet. As shown in Fig. 1, the mutually exclusive events for the transmission of primary packet P1 can be defined as follows:

$\mathcal{C}_{\mathcal{I}}$ = {PT receives ACK1 after the packet P1 is transmitted for t-th, $t \in \{1, 2, \ldots, K\}$}. Under this event, as shown in Fig. 1a, b, there are two disjoint events $\{\mathcal{C}_{\mathcal{I}}, \mathcal{C}_{\mathcal{I}r}\}$ and $\{\mathcal{C}_{\mathcal{I}}, \overline{\mathcal{C}}_{\mathcal{I}r}\}$ respectively with and without the cooperation from ST. Event $\mathcal{C}_{\mathcal{I}r}$ represents that n interfering packets are forwarded by ST from the transmission slot between 1 and t, where $\mathcal{C}_{\mathcal{I}r} = \cup_{i=1}^{t} \mathcal{F}_i$. And the complementary event of $\mathcal{C}_{\mathcal{I}r}$ is denoted as $\overline{\mathcal{C}}_{\mathcal{I}r}$.

$\mathcal{C}_{\mathcal{I}\mathcal{L}}$ = {PT does not receive ACK1 after the packet P1 is transmitted for K-th, i.e. P1 is lost}. Similarly, two disjoint events $\{\mathcal{C}_{\mathcal{I}\mathcal{L}}, \mathcal{C}_{\mathcal{I}r}\}$ and $\{\mathcal{C}_{\mathcal{I}\mathcal{L}}, \overline{\mathcal{C}}_{\mathcal{I}r}\}$ are shown in Fig. 1c, d.

In this mode, the received signal at ST can be written as

$$y_{ST}(t) = \sqrt{P_P d_P^{-\alpha}} h_P(t) x_P(t) + \sqrt{P_I d_{IS}^{-\alpha}} h_{IS}(t) x_I(t) + n_0(t), \tag{3}$$

where $n_0(t)$ is the complex white Gaussian noise with zero mean and power N_0, which is the receiver noise at ST. Thus in a time slot, the outage probability of the link IT → ST (i.e. the probability that ST cannot decode the interfering signal from IT) can be written as

$$O_{IS} = \Pr\left\{ R_I > \log_2\left(1 + \frac{P_I d_{IS}^{-\alpha} |h_{IS}|^2}{P_P d_{PS}^{-\alpha} |h_{PS}|^2 + N_0}\right)\right\} = 1 - \frac{P_I d_{IS}^{-\alpha} \exp(-\rho_I N_0/(P_I d_{IS}^{-\alpha}))}{\rho_I P_P d_{PS}^{-\alpha} + P_I d_{IS}^{-\alpha}}, \tag{4}$$

where $\rho_I = 2^{R_I} - 1$. While the outage probability of the link PT → ST (i.e. the probability that ST cannot decode the signal packet of the primary) can be written as

$$O_{PS} = \Pr\left\{ R_P > \log_2\left(1 + \frac{P_P d_{PS}^{-\alpha} |h_{PS}(t)|^2}{P_I d_{IS}^{-\alpha} |h_{IS}(t)|^2 + N_0}\right)\right\} = 1 - \frac{P_P d_{PS}^{-\alpha} \exp(-\rho_P N/(P_P d_{PS}^{-\alpha}))}{\rho_P P_I d_{IS}^{-\alpha} + P_P d_{PS}^{-\alpha}}. \tag{5}$$

It is assumed that interference mitigation is performed at PR if the event $\mathcal{C}_{\mathcal{I}r}$ takes place. Now the received signal at PR can be written as

$$y_{\mathcal{C}_{\mathcal{I}}}(t) = \sqrt{P_P d_P^{-\alpha}} h_P(t) x_P(t) + n(t). \tag{6}$$

Under the condition of the event $\mathcal{C}_{\mathcal{I}r}$ occurs, the outage probability of the link PT → PR in one slot can be written as

$$O_{\mathcal{C}_{\mathcal{I}}} = \Pr\left\{ R_P > \log_2\left(1 + \frac{P_P d_P^{-\alpha} |h_P|^2}{N}\right)\right\} = 1 - \exp\left(-\rho_P N / \left(P_P d_P^{-\alpha} \sigma_P^2\right)\right). \tag{7}$$

ST forwards the interfering packet to PR which can promote the reception of the interference at PR. PR can decode the interfering signal jointly with the primary signal. Thus, compared to the traditional primary system as mentioned in Sect. 2.2, the primary performance is improved by interference mitigation. This improvement throughput of primary will be quantified as credit accumulated by the secondary system. And more detailed analysis of credits is described in Sect. 4. It is known that only as the event $\mathcal{C}_{\mathcal{I}r}$ takes place, the interference mitigation can be performed at PR. Thus, the credits can be collected only in event $\{\mathcal{C}_{\mathcal{I}}, \mathcal{C}_{\mathcal{I}r}\}$.

2.4 Access Mode with Decoding the Interfering Signal

In access mode with decoding the interfering signal, SR constantly monitors the interfering packets and the ACK/NACK feedbacks. The signal from IT is always willing to be decoded by SR. In one time slot, event ξ_r is defined as the state that the interfering signal is decoded successfully by SR, where the interfering signal can be used for interference cancellation during the decoding of the secondary signal. Event $\overline{\xi}_r$ is the complementary event of ξ_r. Event ς_r is defined as the state that SR receives a NACK or no feedback signal from IT. Only as the events ξ_r, ζ and ς_r occur at the same time, the secondary packet can be transmitted by ST. If ST is allowed to transmit the secondary packet to SR that is defined as the event $\mathcal{G}$, where $\mathcal{G} = \xi_r \cap \varsigma_r \cap \zeta$, SR is to broadcast a cooperative-access-transmit (cat) message. Otherwise ST stays silent that is defined as event $\overline{\mathcal{G}}$. And event $\mathcal{G}_i$ is defined as the state that the event $\mathcal{G}$ occurs at the i-th retransmission slot of the primary packet. As shown in Fig. 2, the mutually exclusive events in access mode can be defined as follows:

$\mathcal{A}_{\mathcal{I}} = \{$PT receives ACK1 after the packet P1 is transmitted for t-th, $t \in \{1, 2, \ldots, K\}\}$. Under this event, as shown in Fig. 2a, b, there are two disjoint events $\{\mathcal{A}_{\mathcal{I}}, \mathcal{A}_{\mathcal{I}r}\}$ and $\left\{\mathcal{A}_{\mathcal{I}}, \bar{\mathcal{A}}_{\mathcal{I}r}\right\}$ respectively with and without secondary access. Event $\mathcal{A}_{\mathcal{I}r}$ represents that n secondary packets are transmitted by ST from the transmission slot between 1 and t, where $\mathcal{A}_{\mathcal{I}r} = \cup_{i=1}^{t} \mathcal{G}_i$. And the complementary event of $\mathcal{A}_{\mathcal{I}r}$ is denoted as $\bar{\mathcal{A}}_{\mathcal{I}r}$.

$\mathcal{A}_{\mathcal{I}\mathcal{L}} = \{$PT does not receive ACK1 after the packet P1 is transmitted for K-th, i.e. P1 is lost$\}$. Similarly, two disjoint events $\{\mathcal{A}_{\mathcal{I}\mathcal{L}}, \mathcal{A}_{\mathcal{I}r}\}$ and $\left\{\mathcal{A}_{\mathcal{I}\mathcal{L}}, \bar{\mathcal{A}}_{\mathcal{I}r}\right\}$ are shown in Fig. 2c, d.

In access mode, only as the interfering signals are decoded successfully by SR, the secondary signals can be transmitted. In a time slot, the outage probability of the link IT $\rightarrow$ SR (i.e. the probability that SR cannot decode the interfering signal) can be written as

$$O_{ISR} = \Pr\left\{R_I > \log_2\left(1 + \frac{P_I d_{ISR}^{-\alpha} |h_{ISR}|^2}{P_P d_{PSR}^{-\alpha} |h_{PSR}|^2 + N_0}\right)\right\} = 1 - \frac{P_I d_{ISR}^{-\alpha} \exp(-\rho_I N_0/(P_I d_{ISR}^{-\alpha}))}{\rho_I P_P d_{PSR}^{-\alpha} + P_I d_{ISR}^{-\alpha}}. \tag{8}$$

If the interfering signal is decoded successfully by SR, the received signal at SR can be written as

$$y_{SR}(t) = \sqrt{P_P d_{PSR}^{-\alpha}} h_{PSR}(t) x_P(t) + \sqrt{P_S d_S^{-\alpha}} h_S(t) x_S(t) + n_1(t), \tag{9}$$

where $x_S(t)$ is the transmitted signal symbol from ST with $E\left[|x_S(t)|^2\right] = 1.n_1(t)$ represents the receiver noise at SR, which is the complex white Gaussian noise with zero mean and power N_0. Under the condition that the interfering signal is decoded successfully by SR, the outage probability of the link ST $\rightarrow$ SR (i.e. the probability that secondary packet is not successfully delivered to SR) in one slot can be written as

$$O_S = \Pr\left\{R_S > \log_2\left(1 + \frac{P_S d_S^{-\alpha} |h_S|^2}{P_P d_{PSR}^{-\alpha} |h_{PSR}|^2 + N_0}\right)\right\} = 1 - \frac{P_S d_S^{-\alpha} \exp(-\rho_S N/(P_S d_S^{-\alpha}))}{\rho_S P_P d_{PSR}^{-\alpha} + P_S d_S^{-\alpha}}, \tag{10}$$

where $\rho_S = 2^{R_S} - 1$.

If the event $\mathcal{A}_{\mathcal{I}r}$ occurs in a time slot, the received signal at PR in this mode can be written as

$$y_{\mathcal{A}_{\mathcal{I}}}(t) = \sqrt{P_P d_P^{-\alpha}} h_P(t) x_P(t) + \sqrt{P_S d_{SP}^{-\alpha}} h_{SP}(t) x_S(t) + \sqrt{P_I d_{IP}^{-\alpha}} h_{IP}(t) x_I(t) + n(t). \tag{11}$$

Under the condition of the event $\mathcal{A}_{\mathcal{I}r}$ occurs, the outage probability of the link PT → PR in one slot can be written as

$$O_{\mathcal{A}_{\mathcal{I}}} = \Pr\left\{\frac{P_P d_P^{-\alpha}\left|h_P(t)\right|^2}{P_S d_{SP}^{-\alpha}\left|h_{SP}(t)\right|^2 + P_I d_{IP}^{-\alpha}\left|h_{IP}(t)\right|^2 + N} < \rho_P\right\} = 1 - \frac{\exp(-c)}{(1+a)(1+b)}, \quad (12)$$

where $a = \rho_P P_S d_{SP}^{-\alpha} / \left(P_P d_P^{-\alpha}\right)$, $b = \rho_P P_I d_{IP}^{-\alpha} / \left(P_P d_P^{-\alpha}\right)$, $c = \rho_P N / \left(P_P d_P^{-\alpha}\right)$.

In access mode, during the process of decoding of a primary packet, the secondary packet is regarded as the interference. Thus, compared to the traditional primary system, the primary throughput can be degraded by transmission of the secondary packet and this degradation will be quantified as penalty caused by the secondary system. And more detailed analysis of penalties is described in Sect. 4. In the strong interference scenario, in order to compare the proposed protocol in this paper with the protocol in Ref. [12], the communication system with an interferer in protocol of [12] is investigated in the Sect. 2.5.

2.5 Cooperation Mode and Access Mode in [12]

The main idea of the protocol in Ref. [12] is that the secondary system serves as a relay to assist the primary transmission in cooperation mode and SR decodes the primary signals for interference cancellation in access mode. In this paper, an interferer is considered in the communication system, and the system performance is degraded due to the presence of the interferer, while the interferer is not considered in the protocol of Ref. [12]. Thus, the outage probability is re-derived as follows. When ST relays primary packet to PR, the received signal at PR can be written as

$$y_C(t) = \sqrt{P_S d_{SP}^{-\alpha}}\, h_{SP}(t) x_P(t) + \sqrt{P_I d_{IP}^{-\alpha}}\, h_{IP}(t) x_I(t) + n(t). \quad (13)$$

Under the condition that ST relays primary packet to PR, the outage probability of the link PT → PR in one slot can be written as

$$O_C = \Pr\left\{\frac{P_S d_{SP}^{-\alpha}\left|h_{SP}(t)\right|^2}{P_I d_{IP}^{-\alpha}\left|h_{IP}(t)\right|^2 + N} < \rho_P\right\} = 1 - \frac{P_S d_{SP}^{-\alpha}\exp(-\rho_P N/(P_S d_{SP}^{-\alpha}))}{\rho_P P_I d_{IP}^{-\alpha} + P_S d_{SP}^{-\alpha}}. \quad (14)$$

In access mode with decoding primary signal, only as the primary signals are decoded successfully by SR, the secondary signals can be transmitted by ST. In one time slot, the outage probability of the link PT → SR (i.e. the probability that SR cannot decode the primary signal from PT) can be written as

$$O_{PSR} = \Pr\left\{\frac{P_P d_{PSR}^{-\alpha}\left|h_{PSR}(t)\right|^2}{P_I d_{ISR}^{-\alpha}\left|h_{ISR}(t)\right|^2 + N} < \rho_P\right\} = 1 - \frac{P_P d_{PSR}^{-\alpha}\exp(-\rho_P N/(P_P d_{PSR}^{-\alpha}))}{\rho_P P_I d_{ISR}^{-\alpha} + P_P d_{PSR}^{-\alpha}}. \quad (15)$$

Under the condition that the secondary signals can be transmitted by ST, the outage probability of the link PT → PR in one slot equal to 1. And in a time slot, the outage probability of the link ST → SR (i.e. the probability that a secondary packet is not successfully delivered to SR) can be written as

$$O_{S0} = \Pr\left\{R_S > \log_2\left(1 + \frac{P_S d_S^{-\alpha}\left|h_S\right|^2}{P_I d_{ISR}^{-\alpha}\left|h_{ISR}\right|^2 + N_0}\right)\right\} = 1 - \frac{P_S d_S^{-\alpha}\exp(-\rho_S N/(P_S d_S^{-\alpha}))}{\rho_S P_I d_{ISR}^{-\alpha} + P_S d_S^{-\alpha}}. \quad (16)$$

3 The Throughput Analysis

The operation process of the system with type-I HARQ is described in Sect. 2.1. The definition of the primary throughput is the same as that in Ref. [12], i.e. the average number of packets successfully delivered per time slot.

$$\eta_P = \frac{\sum_{t=1}^{K} P_t}{\sum_{t=1}^{K} t P_t + K O_P^K} \text{ packets/slot.} \tag{17}$$

In traditional primary communication system with an interferer, which is described in Sect. 2.2, the probability that PT can receive an ACK after the primary packet is transmitted for t-th is denoted as $P_t = O_P^{t-1}(1 - O_P)$, where $t \in \{1, 2, \ldots, K\}$. Thus, the throughput of the primary in the traditional system can be written as Eq. (17).

The cooperation mode with forwarding interference is described in Sect. 2.3. The number of retransmission of one-primary-packet and one-interfering-packet is independent of each other in a time slot. The probability that the IT can receive an ACK after the interfering packet is transmitted for t_I-th is denoted as $P_I = O_I^{t_I - 1}(1 - O_I)$, where $t_I \in \{1, 2, \ldots, K_I\}$, and O_I is calculated by the secondary user to statistic the ACK/NAK feedbacks from IR in a long-term. If the event ξ did not occur in 1–t_I time slots, it is described as event ϖ, otherwise the event ξ may occur in the slot t_S, $t_S \in \{1, 2, \ldots, t_I\}$. If IT does not receive an ACK from IR after the interfering packet is transmitted for K_I-th, i.e. the interfering packet is lost, which is described as event ε, therwise IT may receive an ACK from IR after the interfering packet is transmitted for t_I-th, $t_I \in \{1, 2, \ldots, K_I\}$. Event $\mathcal{O}$ represents that the communication of the link PT $\rightarrow$ PR is an outage. In cooperation mode with forwarding interference, the outage probability of the link PT $\rightarrow$ PR in one slot can be written as

$$\begin{aligned}
O_{\mathcal{PC_I}} &= \sum_{j=1}^{K_I} \left[\sum_{i=1}^{j} \left\{ \Pr\left\{ \mathcal{O} | \bar{\mathcal{C}}_{\mathcal{I}r}, \mathrm{t}_I = j, \mathrm{t}_S = i \right\} \Pr\left\{ \bar{\mathcal{C}}_{\mathcal{I}r} \,|\mathrm{t}_I = j, \mathrm{t}_S = i \right\} \right.\right. \\
&\quad \left. + \Pr\left\{ \mathcal{O} | \mathcal{C}_{\mathcal{I}r}, \mathrm{t}_I = j, \mathrm{t}_S = i \right\} \Pr\left\{ \mathcal{C}_{\mathcal{I}r} \,|\mathrm{t}_I = j, \mathrm{t}_S = i \right\} \right\} \\
&\quad \left. \times \Pr\left\{ \mathrm{t}_S = i \,|\mathrm{t}_I = j \right\} + \Pr\left\{ \mathcal{O} \,|\mathrm{t}_I = j, \varpi \right\} \Pr\left\{ \varpi \,|\mathrm{t}_I = j \right\} \right] \Pr\left\{ \mathrm{t}_I = j \right\} \\
&\quad + \left[\Pr\left\{ \mathcal{O} \,|\varepsilon\,, \varpi \right\} \Pr\left\{ \varpi \,|\varepsilon \right\} + \sum_{i=1}^{K_I} \Pr\left\{ \mathrm{t}_S = i \,|\varepsilon \right\} \right. \\
&\quad \times \left\{ \Pr\left\{ \mathcal{O} | \bar{\mathcal{C}}_{\mathcal{I}r}, \varepsilon\,, \mathrm{t}_S = i \right\} \Pr\left\{ \bar{\mathcal{C}}_{\mathcal{I}r} \,|\varepsilon\,, \mathrm{t}_S = i \right\} \right. \\
&\quad \left. \left. + \Pr\left\{ \mathcal{O} | \mathcal{C}_{\mathcal{I}r}, \varepsilon\,, \mathrm{t}_S = i \right\} \Pr\left\{ \mathcal{C}_{\mathcal{I}r} \,|\varepsilon\,, \mathrm{t}_S = i \right\} \right\} \right] \Pr\left\{ \varepsilon \right\} \\
&= \sum_{j=1}^{K_I} \left\{ \sum_{i=1}^{j} \left(\frac{i}{j} O_P + \frac{j-i}{j} O_{\mathcal{C_I}} \right) \left[O_{IS}^{i-1}(1 - O_{IS}) \right] + O_P O_{IS}^{j} \right\} \left[O_I^{j-1}(1 - O_I) \right] \\
&\quad + O_I^{K_I} \left\{ \sum_{i=1}^{K_I} \left(\frac{i}{K_I} O_P + \frac{K_I - i}{K_I} O_{\mathcal{C_I}} \right) \left[O_{IS}^{i-1}(1 - O_{IS}) \right] + O_P O_{IS}^{K_I} \right\}
\end{aligned} \tag{18}$$

Thus, the probabilities of occurrence of the event $\mathcal{C}_{\mathcal{I}}$ and $\mathcal{C}_{\mathcal{IL}}$ can be respectively written as

$$\Pr\{\mathcal{C}_{\mathcal{I}}\} = (1 - O_{\mathcal{PC}_{\mathcal{I}}})O_{\mathcal{PC}_{\mathcal{I}}}^{t-1} \text{ and } \Pr\{\mathcal{C}_{\mathcal{IL}}\} = O_{\mathcal{PC}_{\mathcal{I}}}^{K}. \tag{19}$$

The throughput of the primary in cooperation mode with forwarding interference can be written as Eq. (20).

$$\eta_{\mathcal{C}_{\mathcal{I}}} = \frac{\sum_{t=1}^{K}\Pr\{\mathcal{C}_{\mathcal{I}}\}}{\sum_{t=1}^{K} t\Pr\{\mathcal{C}_{\mathcal{I}}\} + K\Pr\{\mathcal{C}_{\mathcal{IL}}\}} = \frac{\sum_{t=1}^{K}(1 - O_{\mathcal{PC}_{\mathcal{I}}})O_{\mathcal{PC}_{\mathcal{I}}}^{t-1}}{\sum_{t=1}^{K} t(1 - O_{\mathcal{PC}_{\mathcal{I}}})O_{\mathcal{PC}_{\mathcal{I}}}^{t-1} + K\,O_{\mathcal{PC}_{\mathcal{I}}}^{K}} \text{packets/slot.} \tag{20}$$

The access mode with decoding the interfering signal is described in Sect. 2.4. If the event ξ_r did not occur in 1–t_I time slots, it is described as event ϖ_r, otherwise, and then the event ξ_r may occur in the slot t_{Sr}, $t_S \in \{1, 2, \ldots, t_I\}$. Event $\mathcal{O}_{\mathcal{S}}$ represents that the communication of the link ST → SR is an outage. In access mode with decoding the interfering signal, the outage probability of the link ST → SR in one slot can be written as

$$\begin{aligned}
O_{\mathcal{SA}_{\mathcal{I}}} &= \sum_{j=1}^{K_I}\left[\sum_{i=1}^{j}\left\{\Pr\left\{\mathcal{O}_{\mathcal{S}}\middle|\,\bar{\mathcal{A}}_{\mathcal{I}r}, \mathrm{t}_I = j, \mathrm{t}_S = i\right\}\Pr\left\{\bar{\mathcal{A}}_{\mathcal{I}r}\,|\mathrm{t}_I = j, \mathrm{t}_S = i\right\}\right.\right.\\
&\quad + \Pr\{\mathcal{O}_{\mathcal{S}}|\,\mathcal{A}_{\mathcal{I}r}, \mathrm{t}_I = j, \mathrm{t}_S = i\}\Pr\{\mathcal{A}_{\mathcal{I}r}\,|\mathrm{t}_I = j, \mathrm{t}_S = i\}\}\\
&\quad \left.\times \Pr\{\mathrm{t}_S = i\,|\mathrm{t}_I = j\} + \Pr\{\mathcal{O}_{\mathcal{S}}\,|\mathrm{t}_I = j, \varpi_r\}\Pr\{\varpi_r\,|\mathrm{t}_I = j\}\right]\Pr\{\mathrm{t}_I = j\}\\
&\quad + \left[\Pr\{\mathcal{O}_{\mathcal{S}}\,|\varepsilon\,, \varpi_r\}\Pr\{\varpi_r\,|\varepsilon\} + \sum_{i=1}^{K_I}\Pr\{\mathrm{t}_S = i\,|\varepsilon\}\right.\\
&\quad \times \left\{\Pr\left\{\mathcal{O}_{\mathcal{S}}\middle|\,\bar{\mathcal{A}}_{\mathcal{I}r}, \varepsilon\,, \mathrm{t}_S = i\right\}\Pr\left\{\bar{\mathcal{A}}_{\mathcal{I}r}\,|\varepsilon\,, \mathrm{t}_S = i\right\}\right.\\
&\quad \left.+ \Pr\{\mathcal{O}_{\mathcal{S}}|\,\mathcal{A}_{\mathcal{I}r}, \varepsilon\,, \mathrm{t}_S = i\}\Pr\{\mathcal{A}_{\mathcal{I}r}\,|\varepsilon\,, \mathrm{t}_S = i\}\}\right]\Pr\{\varepsilon\}\\
&= \sum_{j=1}^{K_I}\left\{\sum_{i=1}^{j}\left(\frac{i}{j} + \frac{j-i}{j}O_S\right)\left[O_{ISR}^{i-1}(1 - O_{ISR})\right] + O_{ISR}^{j}\right\}\left[O_I^{j-1}(1 - O_I)\right]\\
&\quad + O_I^{K_I}\left\{\sum_{i=1}^{K_I}\left(\frac{i}{K_I} + \frac{K_I - i}{K_I}O_S\right)\left[O_{ISR}^{i-1}(1 - O_{ISR})\right] + O_{ISR}^{K_I}\right\}
\end{aligned} \tag{21}$$

The outage probability of the link PT → PR in one slot can be written as

$$\begin{aligned}
O_{\mathcal{PA}_{\mathcal{I}}} &= \sum_{j=1}^{K_I}\left[\sum_{i=1}^{j}\left\{\Pr\left\{\mathcal{O}\middle|\,\bar{\mathcal{A}}_{\mathcal{I}r}, \mathrm{t}_I = j, \mathrm{t}_S = i\right\}\Pr\left\{\bar{\mathcal{A}}_{\mathcal{I}r}\,|\mathrm{t}_I = j, \mathrm{t}_S = i\right\}\right.\right.\\
&\quad + \Pr\{\mathcal{O}|\,\mathcal{A}_{\mathcal{I}r}, \mathrm{t}_I = j, \mathrm{t}_S = i\}\Pr\{\mathcal{A}_{\mathcal{I}r}\,|\mathrm{t}_I = j, \mathrm{t}_S = i\}\}\\
&\quad \left.\times \Pr\{\mathrm{t}_S = i\,|\mathrm{t}_I = j\} + \Pr\{\mathcal{O}\,|\mathrm{t}_I = j, \varpi_r\}\Pr\{\varpi_r\,|\mathrm{t}_I = j\}\right]\Pr\{\mathrm{t}_I = j\}\\
&\quad + [\Pr\{\mathcal{O}\,|\varepsilon\,, \varpi_r\}\Pr\{\varpi_r\,|\varepsilon\} + \sum_{i=1}^{K_I}\Pr\{\mathrm{t}_S = i\,|\varepsilon\}
\end{aligned}$$

$$\times \left\{\Pr\left\{\mathcal{O}|\,\bar{\mathcal{A}}_{\mathcal{I}r},\varepsilon\,,\mathrm{t}_S=i\right\}\Pr\left\{\bar{\mathcal{A}}_{\mathcal{I}r}\,|\varepsilon\,,\mathrm{t}_S=i\,\right\}\right.$$
$$+\Pr\{\mathcal{O}|\,\mathcal{A}_{\mathcal{I}r},\varepsilon\,,\mathrm{t}_S=i\}\Pr\{\mathcal{A}_{\mathcal{I}r}\,|\varepsilon\,,\mathrm{t}_S=i\,\}\}]\Pr\{\varepsilon\}$$
$$=\sum_{j=1}^{K_I}\left\{\sum_{i=1}^{j}\left(\frac{i}{j}O_P+\frac{j-i}{j}O_{\mathcal{A}_\mathcal{I}}\right)\left[O_{ISR}^{i-1}(1-O_{ISR})\right]+O_PO_{ISR}^{j}\right\}\left[O_I^{j-1}(1-O_I)\right]$$
$$+O_I^{K_I}\left\{\sum_{i=1}^{K_I}\left(\frac{i}{K_I}O_P\;+\frac{K_I-i}{K_I}O_{\mathcal{A}_\mathcal{I}}\right)\times\left[O_{ISR}^{i-1}(1-O_{ISR})\right]+O_PO_{ISR}^{K_I}\right\} \tag{22}$$

The probability of occurrence of the event $\mathcal{A}_\mathcal{I}$ and $\mathcal{A}_{\mathcal{I}\mathcal{L}}$ can be respectively written as

$$\Pr\{\mathcal{A}_\mathcal{I}\}=(1-O_{\mathcal{P}\mathcal{A}_\mathcal{I}})O_{\mathcal{P}\mathcal{A}_\mathcal{I}}^{t-1}\text{ and }\Pr\{\mathcal{A}_{\mathcal{I}\mathcal{L}}\}=O_{\mathcal{P}\mathcal{A}_\mathcal{I}}^{K}. \tag{23}$$

Thus, the throughput of the primary in access mode with decoding the interfering signal can be written as

$$\eta_{\mathcal{A}_\mathcal{I}}=\frac{\sum_{t=1}^{K}\Pr\{\mathcal{A}_\mathcal{I}\}}{\sum_{t=1}^{K}t\Pr\{\mathcal{A}_\mathcal{I}\}+K\Pr\{\mathcal{A}_{\mathcal{I}\mathcal{L}}\}}=\frac{\sum_{t=1}^{K}(1-O_{\mathcal{P}\mathcal{A}_\mathcal{I}})O_{\mathcal{P}\mathcal{A}_\mathcal{I}}^{t-1}}{\sum_{t=1}^{K}t(1-O_{\mathcal{P}\mathcal{A}_\mathcal{I}})O_{\mathcal{P}\mathcal{A}_\mathcal{I}}^{t-1}+KO_{\mathcal{P}\mathcal{A}_\mathcal{I}}^{K}}\text{packets/slot.} \tag{24}$$

In this mode, only as the event $\mathcal{A}_{\mathcal{I}r}$ occurs, the secondary packet is allowed to be transmitted from ST to SR. Then the throughput of the secondary can be written as

$$\eta_S=1-O_{\mathcal{S}\mathcal{A}_\mathcal{I}}\text{packets/slot.} \tag{25}$$

Due to the presence of an interferer in this paper, the outage probability of each communication links is different from that in Ref. [12]. The outage probabilities O_P, O_{PS}, $O_\mathcal{C}$, O_{PSR} and O_{S0} in this paper correspond to the outage probabilities O_1, O_2, O_3, O_4 and O_5 in Ref. [12], respectively. By substituting O_P, O_{PS} and $O_\mathcal{C}$ into Eqs. (18–eq21) in Ref. [12], the throughput of the primary in cooperation mode with relaying the primary packet can be obtained. By substituting O_P, O_{PS} into Eqs. (23–27) in Ref. [12], the throughput of the primary in access mode with decoding the primary signal can be obtained. And by substituting those five outage probabilities into Eqs. (29), (30), the throughput of the secondary can be obtained. Comparative analyses of those throughputs and the throughputs obtained by (20) (24) (25) in this paper are presented in Sect. 5.

4 Credit System for the Spectrum Sharing Protocol with Forwarding Interference

Similar to [12], in cooperation mode with forwarding interference, credits accumulated by the secondary system are quantified as the gains of the primary throughput during cooperation mode compared to the traditional primary system. Thus, the mathematical model of credit can be expressed as follow:

$$\mathcal{C}=\eta_{\mathcal{C}_\mathcal{I}}-\eta_P\text{ credits/slot.} \tag{26}$$

In access mode with decoding the interfering signal, the penalties incurred by the secondary spectrum access are quantified as the degradation of the primary throughput in access mode over the traditional primary system. Thus, the mathematical model of penalty can be expressed as follow:

$$\mathcal{P} = \eta_P - \eta_{\mathcal{A}_\mathcal{I}} \text{ penalties/slot.} \tag{27}$$

And the ratio between the penalties and credits can be obtained by

$$\gamma = \frac{\mathcal{P}}{\mathcal{C}} = \frac{\eta_P - \eta_{\mathcal{A}_\mathcal{I}}}{\eta_{\mathcal{C}_\mathcal{I}} - \eta_P}. \tag{28}$$

In the effective protocol, the system performance of the primary must not be worse than the traditional primary system, in which secondary user does not exist. In the proposed protocol, the entire transmission times of the primary system is divided into two parts. One is the cooperation time, in which the secondary system operates on the cooperation mode, which is denoted by $t_{\mathcal{C}_\mathcal{I}}$. The other is the access time, in which the secondary system operates on the access mode, is denoted by $t_{\mathcal{A}_\mathcal{I}}$. Thus, the overall average primary throughput in the proposed protocol is obtained as

$$T_P = t_{\mathcal{C}_\mathcal{I}} \eta_{\mathcal{C}_\mathcal{I}} + t_{\mathcal{A}_\mathcal{I}} \eta_{\mathcal{A}_\mathcal{I}} \geq \eta_P \text{ packets/slot,} \tag{29}$$

where $t_{\mathcal{C}_\mathcal{I}} + t_{\mathcal{A}_\mathcal{I}} = 1$, and values of $t_{\mathcal{C}_\mathcal{I}}$ and $t_{\mathcal{A}_\mathcal{I}}$ must satisfy the inequality in (29), i.e. $\frac{\gamma}{1+\gamma} \leq t_{\mathcal{C}_\mathcal{I}} \leq 1$. Then, the performances of the primary will not be degraded by the secondary spectrum access in this case. And the overall average secondary throughput in the proposed protocol can be written as

$$T_S = t_{\mathcal{A}_\mathcal{I}} \eta_S \leq \frac{1}{1+\gamma} \eta_S \text{ packets/slot.} \tag{30}$$

In order to satisfy the QoS (Quality of Service) of the secondary user, the minimum achievable throughput is fixed as $\widehat{T}_S$. To make the cooperation between the secondary and the primary has significance, $\widehat{T}/\eta_S$ must be smaller than $1/(1+\gamma)$. Thus, in order to meet the QoS of the secondary user and not degrade the performance of the primary user, the following inequality must to be satisfied

$$\frac{\gamma}{1+\gamma} \leq t_{\mathcal{C}_\mathcal{I}} \leq \frac{\eta_P}{\eta_{\mathcal{C}_\mathcal{I}}} - \frac{\eta_{\mathcal{A}_\mathcal{I}}}{\eta_{\mathcal{C}_\mathcal{I}}} \frac{\widehat{T}_S}{\eta_S} \tag{31}$$

5 Numerical Results

In this section, the simulation mainly compares the throughput of the primary and secondary system under the proposed protocol in this paper and the protocol in [12]. The cooperation between the primary and secondary system is achieved by forwarding interference and relaying the primary packet in the former protocol and the latter protocol, respectively. The simulation parameters are defined as follows: $d_P = 1, d_{PS} = 1, d_S = 0.5, d_{IP} = 0.8, d_{IS} = 0.6, d_{SP} = 0.5, d_{ISR} = 0.7$ and $d_{PSR} = 1$, which denote the length of links PT $\rightarrow$ PR, PT $\rightarrow$ ST, ST $\rightarrow$ SR, IT $\rightarrow$ PR, IT $\rightarrow$ ST, ST $\rightarrow$ PR, IT $\rightarrow$ SR and PT $\rightarrow$ SR, respectively. $\alpha = 3$ is the path loss exponent. $R_P = 2$ bit/s/Hz, $R_S = 1$ bit/s/Hz and $R_I = 4$ bit/s/Hz are the minimum achievable rate of the primary, secondary and interfering user, respectively. $K = 5$ and $K_I = 10$ are the maximum number of retransmissions for each packet of the primary and interfering respectively. The outage probability of the

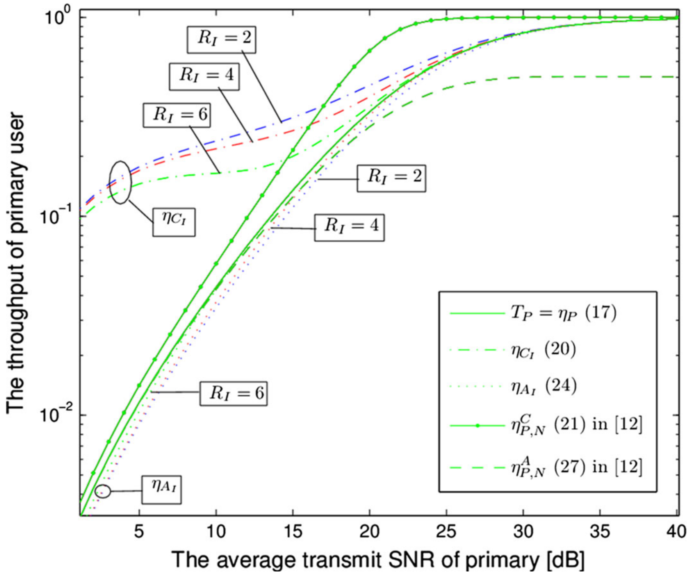

Fig. 3 The primary throughput in five different modes with $R_I = 2, 4, 6$ bit/s/Hz

interfering user in a slot is fixed as $O_I = 0.3$. The average transmit SNR of the secondary and interfering user are $P_S/N_0 = 20$ and $P_I/N_0 = 20$, respectively.

Figure 3 shows the throughput of the primary user versus SNR at the PT in the traditional primary system, cooperation mode with forwarding interference, access mode with decoding the interfering signal, cooperation mode with relaying the primary packet and access mode with decoding the primary signal. The special parameter is $R_I = 2, 4, 6$ bit/s/Hz, and the other parameters are fixed as above. As described in Fig. 3, the primary throughput in cooperation mode with forwarding interference is always larger than that in traditional primary system, and the latter is always larger than the primary throughput in access mode with decoding the interfering signal, i.e. $\eta_{\mathcal{C_I}} \geq \eta_P \geq \eta_{\mathcal{A_I}}$. These numerical results are consistent with the theoretical results in Sect. 3. The former inequality is caused by interference elimination of PR after the interfering packet is forwarded successfully to PR from ST. These results show that, in cooperation mode with forwarding interference, the primary performance is improved and credits are collected by the secondary system. The latter inequality incurred by that the primary performance is degraded by the transmission of the secondary packet. Similarly, the primary throughput in cooperation mode with relaying the primary packet is always larger than that in traditional primary system, and the latter is always larger than the primary throughput in access mode with decoding the primary signal, i.e. $\eta^{\mathcal{C}}_{P,N} \geq \eta_P \geq \eta^{\mathcal{A}}_{P,N}$. Those results agree with the results in [12].

$T_P = \eta_P$, $\eta^{\mathcal{C}}_{P,N}$ and $\eta^{\mathcal{A}}_{P,N}$ always have the same values for different R_I. That is because the three variables may be associated with parameters: $d_{IP}, d_{IS}, d_{SP}, d_{ISR}, P_I/N_0$, and uncorrelated to R_I. In the proposed protocol, ST and SR are always willing to decode the signal from IT, but the transmission of the primary packets can interfere the decoding. In the primary SNR region $P_P/N < 15$ as shown in Fig. 3, the transmission of the primary packets has a very little impact on the decoding of the interfering packet at ST/SR. Thus, the probability that the interfering packet is decoded successfully at ST/SR increases with the decrease of R_I. In other words, with the same interfering SNR, when the values of R_I is small, ST has more opportunities to forward the interfering signal and transmit the secondary packets. Therefore, with an increase from $R_I = 2$ to $R_I = 6$, the primary throughput decreases in cooperation mode with forwarding interference, and increases in access mode with decoding the interfering packet. In the primary SNR region $P_P/N > 15$, the interfering packet is very difficult to be decoded by ST/SR due to the transmission of the primary packets, i.e. the probability that the interfering packet can be decoded successfully by ST/SR is very small. Thus, ST has fewer opportunities to forward the interfering packet and transmit the secondary packet, which brings about that $\eta_{\mathcal{C}_\mathcal{I}}$ and $\eta_{\mathcal{A}_\mathcal{I}}$ are very close to η_P.

Due to the interference from IT, the primary system may suffer a poor performance, and the cooperation from the secondary system is needed in the low primary SNR region $P_P/N < 25$. In the primary SNR region $P_P/N < 15$ as shown in Fig. 3, since the primary SNR is too small, the primary packet is always not decoded successfully at ST/SR. Thus, ST has fewer opportunities to relay the primary packet and transmit the secondary packet in the protocol of [12], which brings about that $\eta^{\mathcal{C}}_{P,N}$ and $\eta^{\mathcal{A}}_{P,N}$ are very close to η_P. On the contrary, the interfering packet is easily to be decoded by ST/SR in this case. Thus, opportunities of ST forwarding the interfering packet are more than opportunities of ST relaying the primary packet, and opportunities of ST transmitting secondary packet in the proposed protocol are more than those in the protocol of [12]. And the results $\eta_{\mathcal{C}_\mathcal{I}} \geq \eta^{\mathcal{C}}_{P,N} \geq \eta^{\mathcal{A}}_{P,N} \geq \eta_{\mathcal{A}_\mathcal{I}}$ are obtained. In other words, this result represents that compared with the protocol of [12], the proposed protocol can be more effective to improve the primary system performance in this region. In the primary SNR region $15 < P_P/N < 25$ as shown in Fig. 3, ST/SR is easier to decode the primary packet than to decode the interfering packet. Thus, ST has more opportunities to relay the primary packet than to forward the interfering packet. As a result, $\eta_{\mathcal{C}_\mathcal{I}}$ is smaller than $\eta^{\mathcal{C}}_{P,N}$. This result represents that compared to the proposed protocol the protocol of [12] can be more effective to improve the primary system performance in this region. In the high primary SNR region $25 < P_P/N$ as shown in Fig. 3, a perfect performance is achieved by the primary system, and the cooperation from secondary is unnecessary for the primary system. As a result, $\eta^{\mathcal{C}}_{P,N}$ and $\eta_{\mathcal{C}_\mathcal{I}}$ is close to $\eta_{\mathcal{C}_\mathcal{I}}$ in this case. And the secondary user is not allowed to share the spectrum with the primary user.

Figure 4 shows the secondary throughput for the proposed protocol and the protocol of [12] with $R_I = 2, 4, 6$ bit/s/Hz. The parameters of this figure are the same as those of Fig. 3. $\eta^{\mathcal{A}}_S$ and $T_{S,N}$ in [12] always have the same values with different R_I, because the two are uncorrelated to R_I. Corresponded to the different values of parameter R_I, T_S and $T_{S,N}$ are always greater than η_S and $\eta^{\mathcal{A}}_S$ respectively. This phenomenon can be explained by (30). In the proposed protocol, SR is always willing to decode the packet from IT, and the transmission of the PT acts as the interference source. The probability that the interfering packet is decoded successfully by SR, decreases with the increase of P_P/N. As a result, the opportunities of ST transmitting the secondary packet decrease with the increase of P_P/N. Thus, T_S and η_S are decrease with the increase of P_P/N. The trends of $T_{S,N}$ and $\eta^{\mathcal{A}}_S$ in Fig. 4 agree with those in Fig. 9 of [12], but the peak of $T_{S,N}$ occurs at $P_P/N = 25$, this difference is caused by the interferer is considered in this paper. For the same value of P_P/N, T_S and η_S decrease with the increase of R_I. Thus, with an increase from $R_I = 2$ to $R_I = 6$, the secondary throughput decreases in access mode with decoding the interfering packet.

In the primary SNR region $P_P/N < 15$ as shown in Fig. 4, SR/ST is easy to decode the interfering packet, because lower primary SNR causes smaller interference on the interfering packet to be decoded at SR/ST. Therefore, the ST has more opportunities to transmit the secondary packet in access mode with decoding the interfering signal. Conversely, it is difficult to decode the primary packet in this region. And the ST has fewer opportunities to transmit the secondary packet in access mode with decoding the primary signal. As a result,

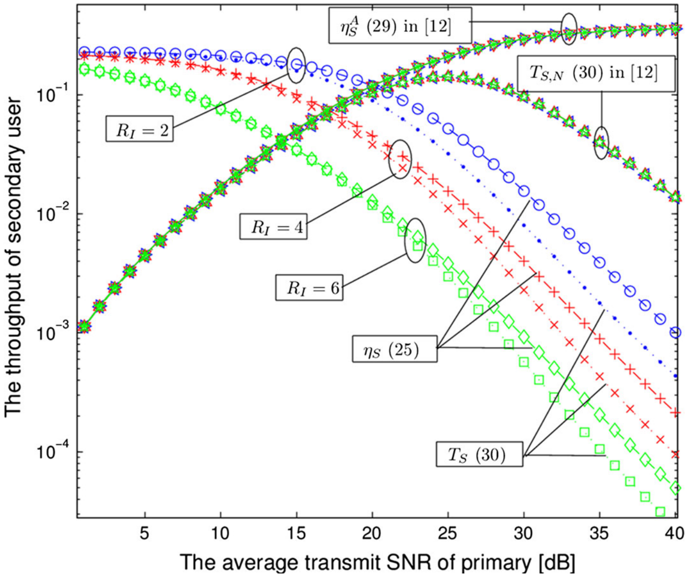

Fig. 4 The secondary throughput for two protocols with $R_I = 2, 4, 6$ bit/s/Hz

$\eta_S^{\mathcal{A}}$ is smaller than η_S. This result represents that compared with the protocol of [12], the proposed protocol can be more effective to improve the secondary system performance in the primary SNR region $P_P/N < 15$. In the primary SNR region $P_P/N > 15$ as shown in Fig. 4, it is difficult to decode the interfering packet at SR/ST, because the higher primary SNR causes signification interference on the interfering packet decoding at SR/ST. Thus, ST has fewer opportunities to transmit the secondary packet in access mode with decoding the interfering signal. Conversely, SR is easy to decode the primary packet in this region. And the ST has more opportunities to transmit the secondary packet in access mode with decoding the primary signal. As a result, $\eta_S^{\mathcal{A}}$ is larger than η_S. This result represents that compared with the proposed protocol, the protocol of [12] can be more effective to improve the secondary system performance in the primary SNR region $P_P/N > 15$.

Figure 5 shows the credits/penalties for the proposed protocol in this paper and the protocol of [12]. The parameters of this figure are the same as those of Fig. 3. The trends of credits and penalties in this figure in cooperation mode with relaying primary packet and access mode with decoding primary packet agree with those in Fig. 8 of [12], but to consider the interferer, the peak of penalties is at $P_P/N = 25$. In the primary SNR region $P_P/N < 15$ as show in Fig. 5, ST/SR is easy to decode the interfering packet. Thus, significant credits can be collected by the secondary system and some penalties can be incurred in the proposed protocol. Because the special parameters are as follows: $d_{PS} = 1$, $d_{IS} = 0.6$, $d_{ISR} = 0.7$ and $d_{PSR} = 1$, credits are larger than penalties. In this case, the secondary and primary systems have a better performance of the proposed protocol. Due to the lower primary SNR region, ST/SR is difficult to decode the primary packet, and few credits can be collected by the secondary system and few penalties can be incurred in the protocol of [12]. Thus, credits and penalties in the proposed protocol are respectively larger than those in the protocol of [12]. In the primary SNR region $P_P/N > 15$ as shown in Fig. 5, very few credits can be collected by the secondary system and few penalties can be incurred in the proposed protocol. In the primary SNR region 25> $P_P/N > 15$ as shown in Fig. 5, significant credits can be collected

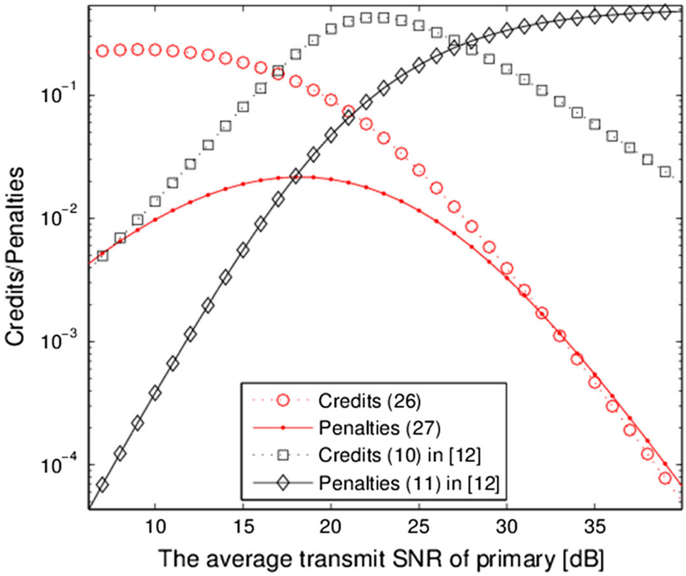

Fig. 5 Credits/penalties for the two protocols

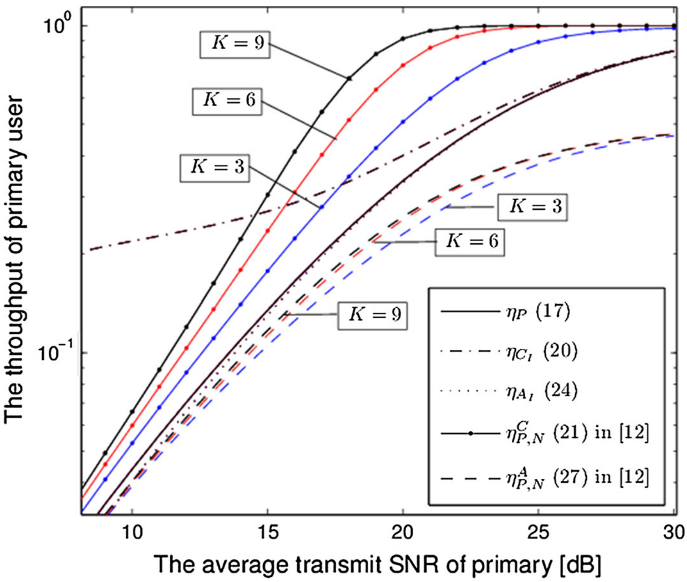

Fig. 6 The primary throughput in five different modes with $K = 3, 6, 9$ bit/s/Hz

by the secondary system, and some penalties can be incurred in the protocol of [12]. In this scenario, the secondary and primary systems have a good performance in the protocol of [12]. In the high primary SNR region $P_P/N > 25$ as shown in Fig. 5, few credits can be collected by the secondary system and few penalties can be incurred in the protocol of [12]. In this case, a perfect performance is achieved by the primary system, and the cooperation from secondary is unnecessary for the primary system. Thus, the secondary user is not allowed to share the spectrum of primary not only in the proposed protocol but also in the protocol in Ref. [12]. These results agree with the results in Fig. 3.

Figure 6 shows the throughput of the primary system versus SNR P_P/N in traditional primary system, cooperation mode with forwarding interference, access mode with decoding the interfering packet, cooperation mode with relaying primary packet and access mode with decoding primary packet. A special parameter of this figure is $K = 3, 6, 9$, and the other parameters are the same as those of Fig. 3. $T_P = \eta_P$, $\eta_{\mathcal{C}_\mathcal{I}}$ and $\eta_{\mathcal{A}_\mathcal{I}}$ always have the same values for different K. That is because the three variables may be associated with K_I, and be irrelevant to K. On the contrary, the probability that the primary packet is decoded successfully at ST/SR, is related to K. And $\eta^{\mathcal{C}}_{P,N}$ and $\eta^{\mathcal{A}}_{P,N}$ increase with the increase of K. These results agree with the results in Fig. 8 of [12], and in which more detailed explanations about the results can be obtained.

6 Conclusion Remark

In this paper, a cooperate-and-access spectrum sharing protocol is proposed where the secondary system switches between cooperation mode with forwarding interference and access mode with decoding the interfering packet. ARQ transport mechanisms in cooperation and access modes are designed. The performance of the secondary and primary is illustrated via throughput analysis. The primary throughputs in cooperation and access modes are derived, and the secondary throughput in access mode is derived from the total probability formula. Credits and penalties are characterized by the primary throughput. When the time that the secondary system operates on cooperation mode is fixed to a minimum, penalties incurred in access mode can be exactly offset by credits collected in cooperation mode, and the primary throughput is the same as that in the traditional primary system. The proposed protocol, the protocol of [12], and the traditional primary communication system with no spectrum sharing are thoroughly analyzed in numerical results. The results show that the primary performances in the three protocols are basically the same in the high primary SNR region. However, the proposed protocol in this paper and the protocol in Ref. [12] can improve the system performance of the primary and secondary than the traditional primary system in the low primary SNR region $P_P/N < 25$. When the average transmits SNR of the primary is lower than that of the interfering user, the proposed protocol is more efficient than the protocol of [12], otherwise the protocol of [12] is more efficient. Thus in the future work, a hybrid protocol where the cooperation mode switches between forwarding interference and relaying primary packet can be proposed.

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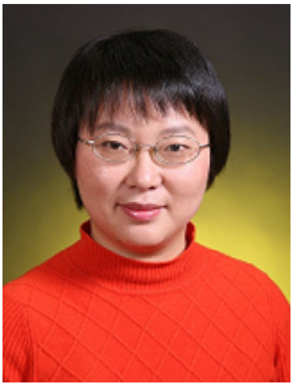
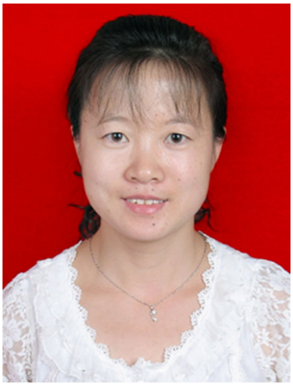
Ping Xie received her doctor degree in 2014 at Beijing University of Posts and Telecommunications, China. Now she is a Lecturer in Henan University of Science and Technology. She received the B.Sc. degree in communication engineering from Kunming University of Science and Technology, Kunming, China, in 2007 and the M.S. degree in communication and information systems from Kunming University of Science and Technology, Kunming, China, in 2011. Her research interests include cognitive radio networks and resource allocation for fading channels.



Lihua Li received her doctor degree in 2004 at Beijing University of Posts and Telecommunications (BUPT), China. She is currently an associate professor in BUPT. Her research focuses on wideband mobile communication technologies including MIMO, link adaptation, cooperative transmission technologies etc. relating to new generation mobile communication systems such as LTE and IMT-Advanced.

Junlong Zhu was born in China, in 1982. He received the B.Sc. degree in communication engineering from Kunming University of Science and Technology, Kunming, China, in 2007 and the M.S. degree in communication and information systems from Kunming University of Science and Technology, Kunming, China, in 2011. From 2011 to now, he is working toward his Ph.D. degree in the State Key Laboratory of Networking and Switching Technology at Beijing University of Posts and Telecommunications. His research interests are in information theory, wireless communications and networking.



Ruijuan Zheng received her doctor degree in 2008 at Harbin Engineering University, Harbin (HEU), China. She is currently an associate professor in Henan University of Science and Technology. Her research interests focuses on network security, Internet of Things, Autonomic Computing, etc.

Mingchuan Zhang received his doctor degree in 2014 at Beijing University of Posts and Telecommunications (BUPT), China. He works as a Lecturer in Henan University of Science and Technology from Mar.2005 to now. His research interests include ad hoc network, Internet of Things, cognitive network and future Internet technology.