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# ARQ-based spectrum sharing with multiple-access secondary system

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**Abstract**

We consider a cognitive radio network in which a multiple-access secondary system coexists with an automatic repeat request (ARQ)-based primary system under heavy primary traffic. To achieve spectrum sharing without degrading the performance of the primary system, the secondary transmitters alternate between cooperation and access modes based on a credit system. In the cooperation mode, the secondary transmitters serve as potential relays among which the best one is selected to help forward the primary packet, thus accumulating credits. These credits will then allow the secondary transmitters to gain spectrum access by exploiting the ARQ mechanism of the primary system.
Our results show that with a cluster of closely located secondary transmitters, the proposed spectrum sharing protocol achieves an equal average throughput for the primary system compared to the case without spectrum sharing, while providing access opportunities for the secondary system. Furthermore, by increasing the number of secondary transmitters or decreasing the distance between secondary transmitters and secondary receiver, an overall higher throughput can be achieved for the secondary system, without affecting the analytical results for the upper bounds of primary throughput under cooperation mode, and secondary throughput under access mode are also derived.

**Keywords:** Cognitive radios, Spectrum sharing, Automatic repeat request, Relay, Multiple-access

## Introduction

Spectrum is a valuable resource in wireless communication systems. Around the world, the frequency spectrum is tightly regulated by fixed spectrum assignment policies which partition the spectrum into a large number of frequency bands and legally limit the applications, users, and operators within each band [1]. This leads to an undesirable situation where some systems may not fully utilize the allocated spectrum while others suffer from a lack of bandwidth. Over the past decades, these challenges and requirements have been extensively studied, giving birth to the notion of cognitive radios [2,3]. Cognitive radio is a technique that improves the utilization of the spectrum by intelligently sharing radio resources among different users, which is also considered in the framework of hierarchical spectrum sharing where the users with different priorities are allowed to operate over the same portion of spectrum.

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With the development of cognitive radio technologies, dynamic spectrum access [4-6] becomes a promising approach to increase the efficiency of spectrum usage. It allows unlicensed wireless users to dynamically access the licensed bands allocated to legacy spectrum holders on a negotiated or an opportunistic basis. The key component of dynamic spectrum access is dynamic spectrum sharing [7-10], which is able to provide efficient and fair spectrum allocation or scheduling solutions between the primary and secondary users.

Three approaches to spectrum sharing between primary and secondary users have been evaluated [11]: spectrum interweave, spectrum underlay, and spectrum overlay. Spectrum interweave is the original idea of utilizing the spectrum holes left by primary system to establish secondary communication links. Spectrum underlay imposes strict constraints on the behavior of the secondary users so that the interference caused to the primary users is limited below a predefined threshold [12]. Spectrum overlay does not necessarily impose restrictions on the transmission power of secondary users, but rather on when and where they may transmit opportunistically without degrading the primary performance [13].

According to spectrum utilization report of FCC [1], there is a large variation in spectrum usage intensity that some bands are heavily used, while others have light usage. When the traffic is light that results in spectrum holes within this band, it is better to use spectrum interweave to allow the secondary access. Conversely, when the traffic is very heavy in this band, where a spectrum hole can be hardly found, spectrum underlay and overlay are better choices.

Cooperative diversity brought about by relay transmissions can effectively combat channel fading and enhance the throughput. It also has a great potential to be adopted in cognitive radio networks [14-22]. Both theoretical and experimental results demonstrate that a relay-assisted cognitive spectrum sharing protocol [16,18] is able to assist the primary system to achieve a better performance and at the same time allows spectrum access for the secondary system. In [17], multi-relay-based cognitive radio networks were considered to improve the performance of secondary users while ensuring the quality of service for primary users. Cooperative spectrum sharing protocol with multiple secondary transmitters was studied in [18]. A two-phase spectrum sharing protocol with cooperative decode-and-forward relaying was proposed in [19], and a spectrum sharing protocol with two-way relaying was proposed in [20]. Cognitive relay networks with multiple primary transceivers under spectrum sharing was considered in [21], where the impact of multiple primary transmitters and receivers on the outage performance of cognitive decode-and-forward relay networks was examined. In [22], the outage probability of dual-hop cognitive amplify-and-forward relay networks subject to Nakagami-m fading is investigated under spectrum sharing environment. In [23], the author analyzed the performance of the secondary user in spectrum sharing cognitive relay networks with the primary user's interference, where the performance loss of the secondary user due to the primary interference can compensate by increase in the number of relays for the secondary system.

Besides the above proposals for spectrum sharing with cognitive relays, the feedback mechanism of automatic repeat request (ARQ)-based primary system has also been exploited to gain secondary spectrum access [24-29]. In [24], the secondary user is able to eavesdrop on the handshaking signals of the ARQ-based primary system and adaptively adjust its input rate such that secondary spectrum sharing is achieved, while maintaining the target rate for the primary user. The interference that the secondary user causes to the primary user and how this interference impacts the retransmission process of the latter were studied in [25]. In [26-29], the authors addressed the coexistence problem by taking advantage of the opportunities that arise during ARQ retransmissions of the primary system. In [26] and [27], the structure of primary ARQ retransmissions is exploited to provide nontrivial rate for the secondary user while minimizing the impact on the primary user. In [28], the secondary user broadcasts a probing signal and listens to the corresponding ACK/NACK sent from the primary receiver and then decides whether to access the spectrum. In [29], a cooperation-and-access spectrum sharing protocol with a single secondary user is proposed where the secondary user alternates between cooperation and access modes by exploiting the ARQ ACK/NACK mechanism of the primary system. Although the basic idea of [29] is similar with our proposed spectrum sharing protocol, there are two major differences. One is that we extend the single secondary transmitter in [29] to multiple secondary transmitters. The other is that they [29] focused on different retransmission times while our work focus on one retransmission. When the multiple secondary transmitters are served as potential relays to help forward the primary packet, the spectrum sharing protocol is much different from the case in [29] with single secondary transmitter. We also derived the analytical upper bound of system throughput for primary and secondary system under cooperation and access mode with multiple secondary transmitters. Our results show that with a cluster of closely located secondary transmitter served as potential relay to help forward the primary packet, an overall higher throughput can be achieved for the secondary system. The secondary throughput gap between the scheme in [29] and our proposed scheme is given in this paper. It was noted that even though ARQ retransmissions may be relatively infrequent, it is still possible to achieve a reasonably good performance for the secondary user.

In this paper, a relay-assisted and ARQ-based spectrum sharing protocol was proposed where the secondary system is configured with multiple secondary transmitters and served as relay to help forward the primary packet. As shown in Figure 1, the primary system consists of a single primary transmitter (PT) and a single primary receiver (PR). On the other hand, the secondary system consists of multiple secondary transmitters (ST) attempting to transmit to a single secondary receiver (SR). To achieve secondary spectrum access without degrading the primary performance, the multiple secondary users will switch between cooperation and access modes based on a credit system. The proposed protocol works efficiently under heavy traffic and switches smartly between cooperation mode and access mode to achieve considerable secondary throughput under heavy traffic mode without degrading the primary performance. We analyze the throughput for the primary and secondary systems and derive theoretical upper bounds for primary throughput in cooperation mode and secondary throughput in access mode. We find the performance gap between the traditional scheme

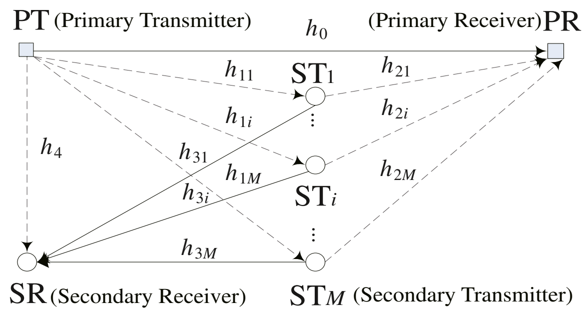


**Figure 1 System model for the proposed spectrum sharing protocol with multiple-access secondary system.**

without relay and the proposed scheme with multiple secondary transmitters serving as potential relay. With the proposed spectrum sharing protocol, it is shown that the secondary system is able to access the spectrum without degrading the primary system performance under heavy traffic and obtain considerable secondary system throughput. With a cluster of closely located secondary transmitters, the secondary system throughput increases with the number of STs and with decreasing distance between STs and SR.

## System model and protocol description

### System model

Consider a cognitive radio system with a stop-and-wait ARQ-based primary system with relay functionality [30], as depicted in Figure 1. The primary system consists of a single PT and PR. The secondary system consists of $M$ secondary transmitters $\mathrm{ST}_i$ where $i \in \mathcal{M} = \{1, 2, ..., M\}$ and a single SR as shown in Figure 1. The channels over links PT→PR, PT→$\mathrm{ST}_i$, $\mathrm{ST}_i$ →PR, $\mathrm{ST}_i$ →SR, and PT→SR are modeled as Rayleigh flat fading with channel coefficients denoted by $h_0, h_{1i}, h_{2i}, h_{3i}$, and $h_4$ respectively. We have $h_0 \sim \mathcal{CN}(0, d_0^{-\nu})$, $h_{ki} \sim \mathcal{CN}(0, d_{ki}^{-\nu})$, $k = 1, 2, 3$, and $h_4 \sim \mathcal{CN}(0, d_4^{-\nu})$, where $\nu$ is the path-loss exponent and $d_0$, $d_{ki}, k = 1, 2, 3$, and $d_4$ are the distances between the respective transmitters and receivers. In order to simplify the theoretical analysis, we assume that the secondary transmitters are closely located and thus we have $d_{ki} = d_k, \forall i \in \mathcal{M}, k = 1, 2, 3$. We also denote the instantaneous channel gains for these links as $\gamma_0 = |h_0|^2$, $\gamma_{ki} = |h_{ki}|^2, k = 1, 2, 3$, and $\gamma_4 = |h_4|^2$. The transmit power at PT and $\mathrm{ST}_i$ is denoted as $P_\mathrm{p}$ and $P_\mathrm{s}$ $\forall i$, respectively. The target rates for the primary and secondary systems are denoted by $R_\mathrm{p}$ and $R_\mathrm{s}$, respectively. The variances of the additive white Gaussian noise at all receivers are assumed to be identical and are denoted as $\sigma^2$.

### Protocol description

In cooperation mode, we quantify the improvement in primary performance due to cooperative relaying from the secondary system as credits accumulated by the secondary system. Each complete transmission for a primary packet in cooperation mode is associated with a credit which is tracked and collected by the secondary system. When enough credits are accumulated by the secondary system to compensate the possible performance loss caused by secondary access, the secondary system turns into access mode.

During access mode, one of the secondary transmitters is allowed to access the spectrum along with the ARQ-based retransmission from PT. When the secondary access is completed, the system returns to cooperation mode again to collect more credits, so on and so forth.

We assume that the transmission of a primary packet is completed within at most two slots, i.e., the maximum number of retransmissions is 1. The secondary system transmits each secondary packet only once with a best-effort mechanism. Since the primary system has heavy traffic, PT is backlogged, i.e., it always has a packet to transmit. The secondary system is also assumed to be backlogged.

The details of the proposed spectrum sharing protocol are described below:

1. In cooperation mode. PT sends a packet to PR in the first time slot while PR, $\mathrm{ST}_i, \forall i \in \mathcal{M}$, and SR attempt to decode this packet. The achievable rate of link PT→PR is given by

$$R_0 = \log_2\left(1 + \frac{P_\mathrm{p}\gamma_0}{\sigma^2}\right). \tag{1}$$

Thus, decoding at PR is successful if $R_0 \geq R_\mathrm{p}$ and the corresponding outage probability of link PT→PR can be expressed as

$$O_0 = \Pr\{R_0 < R_\mathrm{p}\} = 1 - e^{-d_0^{\nu}\frac{(2^{R_\mathrm{p}}-1)\sigma^2}{P_\mathrm{p}}}. \tag{2}$$

If PR successfully decodes the packet, it sends back an ACK. Otherwise, a NACK is sent from PR.
The decoding of the primary packet at $\mathrm{ST}_i, i \in \mathcal{M}$ is successful if $R_{1i} \geq R_\mathrm{p}$, where $R_{1i}$ denotes the achievable rate of link PT →$\mathrm{ST}_i$ and is given by

$$R_{1i} = \log_2\left(1 + \frac{P_\mathrm{p}\gamma_{1i}}{\sigma^2}\right), \tag{3}$$

then the corresponding outage probability for link PT →$\mathrm{ST}_i$ can be written as

$$O_{1i} = O_1 = \Pr\{R_{1i} < R_\mathrm{P}\} = 1 - e^{-d_1^{\nu}\frac{(2^{R_\mathrm{P}}-1)\sigma^2}{P_\mathrm{P}}}. \tag{4}$$

We define $\mathcal{A} = \{R_{1i} \geq R_{\text{p}} | i \in \mathcal{M}\}$, where $\mathcal{A}$ represents the set of secondary transmitters that have successfully decoded the primary packet.
The secondary transmitters will listen to the ACK or NACK message sent from PR. By overhearing these messages, $\text{ST}_i, i \in \mathcal{A}$ is able to estimate the channel gains $\gamma_{2i}, i \in \mathcal{A}$. If an ACK is overheard, $\text{ST}_i, \forall i \in \mathcal{A}$ discards the received primary packet, and PT proceeds to send a new packet. On the other hand, if a NACK is overheard, each secondary transmitter $\text{ST}_i, \forall i \in \mathcal{A}$ starts a count-down timer with initial value

$$t_{2i} = \frac{\Gamma_1}{\gamma_{2i}}, \quad (5)$$

where $\Gamma_1 = \frac{\sigma^2}{P_{\text{s}}} \left(2^{2R_{\text{p}}} - 1\right) t_0$ is the normalization factor and $t_0$ is a predetermined initial time. The $\text{ST}_i$, whose count-down timer reduces to zero first, i.e., $\text{ST}_p, p = \arg\max_{i \in \mathcal{A}} [\gamma_{2i}]$ will broadcast a relay confirmation message (RCM) to identify its presence and then relay the primary packet to PR. In fact, it is the same as selection combining for the primary user. When NACK is heard by PT, it will not retransmit the packet immediately, but instead, it will wait for a predefined duration to see if a RCM is received from any potential relay. When the RCM is heard by PT and all other secondary users $\text{ST}_i, \forall i \in \mathcal{A} \backslash \{p\}$, PT will delegate the retransmission packet and $\text{ST}_i, \forall i \in \mathcal{A} \backslash \{p\}$ will withdraw themselves from the relay contention.
The achievable rate $R_{2i}$ between link $\text{ST}_i \rightarrow$PR is given by

$$R_{2i} = \log_2 \left(1 + \frac{P_{\text{s}} \gamma_{2i}}{\sigma^2}\right). \quad (6)$$

Then the corresponding outage probability for link $\text{ST}_i \rightarrow$PR can be expressed as

$$O_{2i} = O_2 = \Pr\{R_{2i} < R_{\text{p}}\} = 1 - e^{-d_2^{\nu} \frac{(2^{R_{\text{p}}} - 1)\sigma^2}{P_{\text{s}}}}. \quad (7)$$

If $\text{ST}_p$ successfully relays the primary packet to PR, then PR sends back an ACK. If the relayed packet is not successfully decoded by PR, PT will not retransmit this packet but a new packet will be transmitted as the number of retransmission is limited to one.
If a NACK is overheard by $\text{ST}_i, \forall i \in \mathcal{M}$, and PT after the first transmission slot of primary packet, and none of the secondary transmitters has successfully decoded the primary packet, i.e., no RCM is heard by PT within a predefined duration, then PT will retransmit the primary packet in the second time slot. If the packet cannot be decoded at PR after two slots, an outage for primary transmission is declared.
At the same time, SR keeps track of the credits accumulated by secondary system as $N_{\text{C}}$. Each complete transmission for a primary packet in cooperation mode is recorded as a credit earned by the secondary system. The credits accumulated in cooperation mode are used to earn access opportunities for the secondary system in access mode. When enough credits $N_{\text{C}}$ are collected by SR, i.e., $N_{\text{C}} \geq \bar{N}_{\text{C}}$, where $\bar{N}_{\text{C}}$ is the threshold value, a secondary access start message (SASM) is broadcasted by SR and the system turns into access mode. Upon hearing that SASM is sent from SR, $\text{ST}_i, \forall i \in \mathcal{M}$ is able to estimate the channel gains $\gamma_{3i}, \forall i \in \mathcal{M}$.

2. In access mode. When PT transmits a new packet to PR, SR tries to decode the primary packet in anticipation for interference cancelation to be performed to retrieve the secondary packet. The achievable rate $R_4$ between link PT $\rightarrow$SR is given by

$$R_4 = \log_2 \left(1 + \frac{P_{\text{p}} \gamma_4}{\sigma^2}\right). \quad (8)$$

The outage probability for link PT$\rightarrow$SR is given by

$$O_4 = \Pr\{R_4 < R_{\text{p}}\} = 1 - e^{-d_4^{\nu} \frac{(2^{R_{\text{p}}} - 1)\sigma^2}{P_{\text{p}}}}. \quad (9)$$

If SR fails to decode the primary packet in the first transmission slot, we presume that an outage is declared for the secondary transmission. Then the secondary system will operate in cooperation mode for another $\bar{N}_{\text{C}}$ times until it is allowed to access the spectrum again.
After the first transmission, an interference signal (INF) is transmitted by SR to corrupt the corresponding ACK/NACK sent from PR. Since the failure to receive an ACK/NACK is treated as an implicit NACK, PT retransmits the packet in the second transmission slot. At the same time, each secondary transmitter $\text{ST}_i, \forall i \in \mathcal{M}$ now starts a count-down timer with initial value

$$t_{3i} = \frac{\Gamma_2}{\gamma_{3i}}, \quad (10)$$

where $\Gamma_2 = \frac{\sigma^2}{P_{\text{s}}} \left(2^{2R_{\text{s}}} - 1\right) t_0$ is the normalization factor. The $\text{ST}_i$, whose count-down timer reduces to zero first, i.e., $\text{ST}_q, q = \arg\max_{i \in \mathcal{M}} [\gamma_{3i}]$ will send a secondary packet to SR together with a secondary access confirmation message (SACM) to identify its presence. All other secondary users $\text{ST}_i, \forall i \in \mathcal{M} \backslash \{q\}$, upon hearing SACM, will withdraw the access contention. Therefore, the secondary transmitter with the best channel gain exploits the primary retransmission by transmitting to SR simultaneously, with interference cancelation done at SR to retrieve the secondary packet. The achievable rate $R_{3i}$ between link $\mathrm{ST}_i \rightarrow$SR is given by

$$R_{3i} = \log_2\left(1 + \frac{P_s\gamma_{3i}}{\sigma^2}\right). \tag{11}$$

Then the outage probability for link $\mathrm{ST}_i \rightarrow$SR is given by

$$O_{3i} = O_3 = \Pr\{R_{3i} < R_s\} = 1 - e^{-d_3^{\nu}\frac{(2^{R_s}-1)\sigma^2}{P_s}}. \tag{12}$$

In access mode, the secondary packet is transmitted along with the retransmission of the primary packet. Thus the secondary packet is successfully received at SR if $R_{3i} > R_s$. The secondary packet is successfully decoded at SR if $R_{3i} > R_s$ and $R_4 > R_p$. Regardless whether the secondary packet is successfully decoded at SR or not, the system turns into cooperation mode and SR resets $N_C$ to zero.

In access mode, since the secondary system transmits along with the retransmission of primary packets to achieve spectrum access, the retransmission of the primary packets will always fail due to the strong interference from secondary access. Therefore, the successful transmission of primary packets in access mode is dependent only on the first primary transmission. As a result, the primary performance will be severely degraded in access mode.

## Throughput and credit analysis

### Throughput for conventional primary system without relay

For a conventional system based on ARQ mechanism, we consider the scenario where the packet can be transmitted at most by two transmission slots, i.e., only one retransmission. We have the following mutually exclusive events for the transmission of a packet:

Event 1: $C_1$ = {primary packet is successfully received at PR in the first transmission slot}.
Event 2: $C_2$ = {primary packet is not successfully received at PR in the first transmission slot, but the retransmission of the same packet from PT is successfully received at PR}.
Event 3: $C_3$ = {primary packet transmission fails after two transmission slots}.

From (2), the probability of the above events are respectively given by

$$\Pr\{C_1\} = 1 - O_0, \tag{13}$$

$$\Pr\{C_2\} = O_0(1 - O_0), \tag{14}$$

$$\Pr\{C_3\} = O_0^2. \tag{15}$$

Thus, the throughput $\eta_{P_{\text{bits}}}$ is denoted as

$$\eta_{P_{\text{bits}}} = R_P\eta_P, \tag{16}$$

We define $\eta_P$ as the average number of packets successfully delivered per time slot. That is the ratio between how much of each packet that can be successfully delivered and the number of time slots required.

$$\eta_P = \frac{\Pr\{C_1\} + \Pr\{C_2\}}{\Pr\{C_1\} + 2\Pr\{C_2\} + 2\Pr\{C_3\}}. \tag{17}$$

The nominator denotes on average how much of each packet can be successfully delivered, and the denominator denotes the average time slots that are consumed. Therefore, $\eta_P$ is the actual throughput normalized by the bit rate. In this paper, we focus on analyzing the normalized throughput for convenience. Thus, the throughput for the conventional primary system is denoted as

$$\eta_P = 1 - O_0. \tag{18}$$

### Throughput for the primary system in cooperation mode

In cooperation mode, the secondary system is always ready to serve as a relay for the primary system, for which we have the following mutually exclusive events:

Event 1: $E_1$ = {primary packet is successfully received at PR in the first transmission slot}.
Event 2: $E_2$ = {primary packet is not successfully received at PR and $\mathrm{ST}_i, \forall i \in \mathcal{M}$ in the first transmission slot, PT retransmits the same packet in the subsequent slot and it is successfully received at PR}.
Event 3: $E_3$ = {primary packet is not successfully received at PR, but successfully received at one or more $\mathrm{ST}_i, i \in \mathcal{M}$; thus, one ST serves as relay to forward this packet to PR in the subsequent slot and it is successfully received at PR}.
Event 4: $E_4$ = {primary packet transmission fails after two transmission slots}.

From (2) and (4), the probability for $E_1$, $E_2$, and $E_3$ are given by

$$\Pr\{E_1\} = 1 - O_0, \tag{19}$$

$$\Pr\{E_2\} = O_0{O_1}^M(1 - O_0), \tag{20}$$

$$\Pr\{E_3\} = O_0P^{\mathrm{SR}}, \tag{21}$$

where the superscript SR denotes successful relaying, and $P^{\mathrm{SR}}$ represents the joint probability that at least one of the $\mathrm{ST}_i, i \in \mathcal{M}$ successfully receives the primary packet and successfully relays the packet to PR. In other words, $P^{\mathrm{SR}}$ indicates the probability that $k \geq 1$ secondary transmitters can successfully receive the primary packet from PT. Among which, $f \geq 1$ secondary transmitters can successfully relay the primary packet to PR.

We denote $\mathcal{B} = \{\mathrm{ST}_i | i \in \mathcal{M}, R_{1i} > R_p, R_{2i} > R_p\}$, where $\mathcal{B}$ is the set of secondary transmitters $\mathrm{ST}_i, i \in \mathcal{M}$ successfully receiving the primary packet and are able to successfully forward the primary packet to PR in the subsequent slot. Hence, $\mathcal{B} \subseteq \mathcal{A}$. When the first transmission from PT to PR fails, the secondary system selects $\mathrm{ST}_p, p \in \mathcal{A}$ with the best channel gain $p = \arg\max_{i \in \mathcal{A}}[\gamma_{2i}]$ to relay the primary packet. The joint probability $P^{\mathrm{SR}}$ can be expressed as

$$\begin{aligned} P^{\mathrm{SR}} &= \sum_{k=1}^{M}\sum_{f=1}^{k} \Pr\{|\mathcal{A}| = k, |\mathcal{B}| = f\} \\ &= \sum_{k=1}^{M}\sum_{f=1}^{k} \Pr\{|\mathcal{B}| = f \big| |\mathcal{A}| = k\} \Pr\{|\mathcal{A}| = k\}, \end{aligned} \tag{22}$$

and

$$\Pr\{|\mathcal{B}| = f \big| |\mathcal{A}| = k\} = \binom{k}{f}(1-O_2)^f O_2^{(k-f)}, \tag{23}$$

$$\Pr\{|\mathcal{A}| = k\} = \binom{M}{k}(1-O_1)^k O_1^{(M-k)}. \tag{24}$$

Then $P^{\mathrm{SR}}$ is derived as

$$P^{\mathrm{SR}} = \sum_{k=1}^{M}\sum_{f=1}^{k}\binom{M}{k}\binom{k}{f}(1-O_2)^f O_2^{(k-f)}(1-O_1)^k O_1^{(M-k)}. \tag{25}$$

Thus, we have

$$\Pr\{E_3\} = O_0 \sum_{k=1}^{M}\sum_{f=1}^{k}\binom{M}{k}\binom{k}{f}(1-O_2)^f O_2^{(k-f)}(1-O_1)^k O_1^{(M-k)}. \tag{26}$$

$E_4$ represents the outage occurrence, and its probability is given by

$$\Pr\{E_4\} = O_0 O_{1_0}^{MO} + O_0 P^{\mathrm{FR}}, \tag{27}$$

where the first term $O_0 O_{1_0}^{MO}$ denotes the first event that the primary packet fails in the first transmission from PT to PR and all the secondary transmitters $\mathrm{ST}_i, \forall i \in \mathcal{M}$ also fail to decode the primary packet, and the retransmission of the packet from PT to PR fails again. The second term $O_0 P^{\mathrm{FR}}$ denotes the event that the primary packet fails at the first transmission from PT to PR link and the superscript FR denotes failed relaying. So $P^{\mathrm{FR}}$ indicates the joint probability that $k \geq 1$ secondary transmitters can successfully receive the primary packet from PT. Among which, zero secondary transmitters can successfully relay the primary packet to PR. However, at least one of the secondary transmitter $\mathrm{ST}_i, i \in \mathcal{M}$ successfully decodes the primary packet but fails to relay it to PR, i.e., $\mathcal{A} \notin \varnothing$ and $\mathcal{B} \in \varnothing$. Thus, $P^{\mathrm{FR}}$ is also the joint probability that denotes the secondary transmitters successfully receiving the primary packet but failing to relay, for which we have

$$\begin{aligned} P^{\mathrm{FR}} &= \sum_{k=1}^{M} \Pr\{|\mathcal{A}| = k, |\mathcal{B}| = 0\} \\ &= \sum_{k=1}^{M} \Pr\{|\mathcal{B}| = 0 \big| |\mathcal{A}| = k\} \Pr\{|\mathcal{A}| = k\}. \end{aligned} \tag{28}$$

By substituting $f = 0$ into (25), we have from (28)

$$P^{\mathrm{FR}} = \sum_{k=1}^{M}\binom{M}{k}(1-O_1)^k O_1^{(M-k)} {O_2}^k. \tag{29}$$

Therefore,

$$\Pr\{E_4\} = O_0 {O_1}^M O_0 + O_0 \sum_{k=1}^{M}\binom{M}{k}(1-O_1)^k O_1^{(M-k)} {O_2}^k. \tag{30}$$

The throughput for primary system under cooperation mode is thus

$$\begin{aligned} \eta_{\mathrm{C_P}} &= \frac{\Pr\{E_1\} + \Pr\{E_2\} + \Pr\{E_3\}}{\Pr\{E_1\} + 2\Pr\{E_2\} + 2\Pr\{E_3\} + 2\Pr\{E_4\}} \\ &= (1-O_0) + \frac{O_0\left[O_0 P^{\mathrm{SR}} - P^{\mathrm{FR}}(1-O_0)\right]}{1+O_0}. \end{aligned} \tag{31}$$

**Lemma 1.** *An upper bound of $\eta_{\mathrm{C_P}}$ is given by*

$$\begin{aligned} \eta^*_{\mathrm{C_P}} &= \lim_{M\to\infty} \eta_{\mathrm{C_P}} \\ &= (1-O_0) + \frac{O_0^2}{1+O_0}. \end{aligned} \tag{32}$$

*Proof.* Since $P^{\mathrm{SR}} + P^{\mathrm{FR}}$ represents the probability that at least one of the secondary transmitters successfully decodes the primary packet,

$$P^{\mathrm{SR}} + P^{\mathrm{FR}} = 1 - {O_1}^M. \tag{33}$$

From the binomial theorem, $P^{\mathrm{FR}}$ in (29) can be expressed as

$$\begin{aligned} P^{\mathrm{FR}} &= [(1-O_1)O_2 + O_1]^M - O_1^M = (O_2 - O_1 O_2) \\ &\quad \times \Big[(O_2 - O_1 O_2 + O_1)^{M-1} + (O_2 - O_1 O_2 + O_1)^{M-2} O_1 \\ &\quad + (O_2 - O_1 O_2 + O_1)^{M-3} O_1^2 + \ldots + (O_2 - O_1 O_2 + O_1) \\ &\quad \times O_1^{M-2} + O_1^{M-1}\Big], \end{aligned} \tag{34}$$

and

$$P^{\mathrm{SR}} = 1 - [(1-O_1)\, O_2 + O_1]^M. \tag{35}$$

It is clear that $P^{\mathrm{SR}} \to 1$ and $P^{\mathrm{FR}} \to 0$ when $M \to \infty$; hence, the upper bound is obtained. □

### Throughput for primary system in access mode

In access mode, SR transmits an INF signal to corrupt the primary ACK/NACK of the first transmission, and the failure to receive the ACK/NACK is treated as an implicit NACK. Since the secondary transmitter utilizes the retransmission of primary packets to achieve spectrum access, the retransmission of the primary packets will fail due to the strong interference from secondary access. Thus, whether the primary packets can be successfully transmitted or not in access mode is determined by the first transmission slot. There are two mutually exclusive events for primary system in access mode as shown in Figure 2:

Event 1: $A_1$ = {the primary packet is successfully received at PR in the first transmission, but the corresponding ACK is corrupted by SR; PT then retransmits this packet and an ACK is received from PR}.
Event 2: $A_2$ = {the primary packet is not successfully received at PR in the first transmission and the corresponding NACK is corrupted by SR; PT then retransmits this packet but still fails due to the strong interference from the secondary access and a NACK is received at PR, i.e., a packet loss}.

Thus, the probability of the above two events are respectively given by

$$\Pr\{A_1\} = 1 - O_0. \tag{36}$$

$$\Pr\{A_2\} = O_0. \tag{37}$$

The throughput for primary system under access mode thus given by

$$\begin{aligned} \eta_{A_P} &= \frac{\Pr\{A_1\}}{2\Pr\{A_1\} + 2\Pr\{A_2\}} \\ &= \frac{1 - O_0}{2}. \end{aligned} \tag{38}$$

### Credits and penalties

From the above analysis, it is apparent that the throughput for the primary system decreases severely under access mode, but improves significantly under cooperation mode. The performance loss in access mode incurred by the secondary system is regarded as penalties and the performance gain collected by the secondary system in cooperation mode is regarded as credits. Thus we propose an ARQ-based spectrum sharing protocol to regulate the credits and the penalties such that secondary spectrum access can be achieved without degrading the primary performance.

In cooperation mode, 'credits' is defined as

$$\Gamma_C \triangleq \eta_{C_P} - \eta_P \quad \text{(credits/slot)} \tag{39}$$

In access mode, 'penalties' is denoted as

$$\Gamma_P \triangleq \eta_P - \eta_{A_P} \quad \text{(penalties/slot)} \tag{40}$$

It is apparent that the throughput for the conventional system $\eta_P$ is taken as a benchmark in the definition of credits

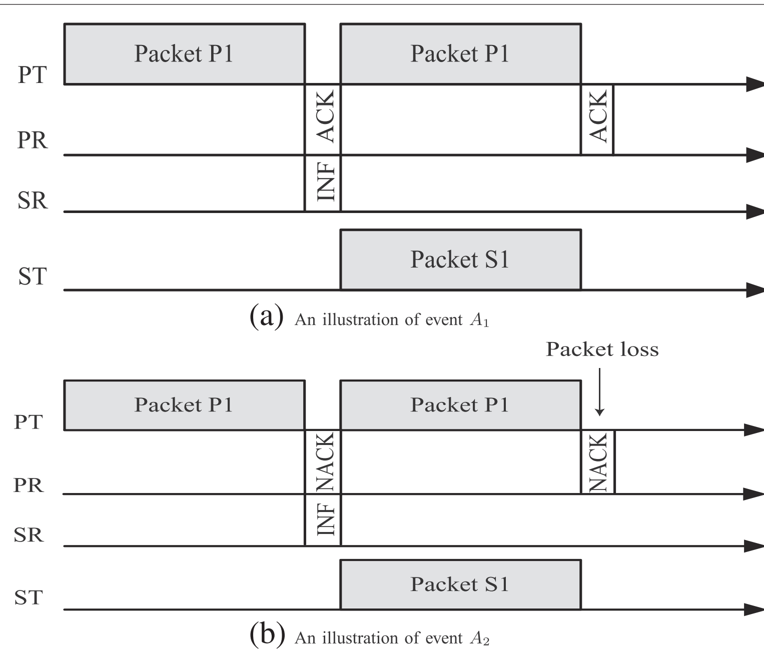


**Figure 2 The ARQ mechanisms in the access mode.** (**a**) An illustration of event A1. (**b**) An illustration of event A2.

and penalties. For ease of exposition, we define the ratio between penalties and credits as

$$\bar{N}_{\mathrm{C}} = \frac{\Gamma_{\mathrm{P}}}{\Gamma_{\mathrm{C}}}. \tag{41}$$

To achieve spectrum sharing without degrading the performance of the primary system, every $\bar{N}_{\mathrm{C}}$ (or $l\bar{N}_{\mathrm{C}}$) complete transmission for a packet in cooperation mode allows one (or $l$) access opportunity for the secondary system, where $l \in \mathbb{Z}^{+}$. Thus, the overall average throughput for primary system in the proposed spectrum sharing protocol is given by

$$\eta_{\mathrm{T_P}} = \eta_{\mathrm{C_P}} \frac{\bar{N}_{\mathrm{C}}}{\bar{N}_{\mathrm{C}}+1} + \eta_{A_{\mathrm{P}}} \frac{1}{\bar{N}_{\mathrm{C}}+1}. \tag{42}$$

### Throughput for secondary system in access mode

For the secondary system, if the primary packet is successfully received at SR in the first transmission, the interference from PT's retransmission can be perfectly canceled out at SR. Otherwise, we assume that the secondary packet fails to be received at SR due to the interference from the primary retransmission. Thus in access mode, there are three mutually exclusive events for the secondary system:

Event 1: $S_1$ = {the primary packet is successfully received at SR in the first transmission slot, and the secondary packet is also successfully received at SR in the second transmission slot}
Event 2: $S_2$ = {the primary packet is successfully received at SR in the first transmission slot, but the secondary packet fails to be received at SR in the second transmission slot}
Event 3: $S_3$ = {the primary packet failed to be received at SR in the first transmission slot}

Thus, the probability of the above three events can be derived as

$$\Pr\{S_1\} = (1-O_4)\left(1-{O_3}^{M}\right), \tag{43}$$

$$\Pr\{S_2\} = (1-O_4){O_3}^{M}, \tag{44}$$

$$\Pr\{S_3\} = O_4. \tag{45}$$

The throughput for the secondary system under access mode is thus given by

$$\begin{aligned}\eta_{\mathrm{S}} &= \frac{\Pr\{S_1\}}{2\Pr\{S_1\}+2\Pr\{S_2\}+2\Pr\{S_3\}} \\ &= \frac{(1-O_4)\left(1-{O_3}^{M}\right)}{2}.\end{aligned} \tag{46}$$

**Lemma 2.** *An upper bound of the secondary throughput under access mode with an increasing M is given by*

$$\begin{aligned}\eta_{\mathrm{S}}^{*} &= \lim_{M\to\infty} \eta_{\mathrm{S}} \\ &= \frac{1-O_4}{2}.\end{aligned} \tag{47}$$

*Proof.* It is clear that ${O_3}^{M} \to 0$ when $M \to \infty$; hence, the upper bound is obtained. □

Through the proposed credit system, the secondary system switches between cooperation and access modes, according to the accumulated credits, continuously. Thus, the overall average throughput for secondary system in the proposed spectrum sharing protocol is given by

$$\eta_{\mathrm{T_S}} = \frac{1}{\bar{N}_{\mathrm{C}}+1}\eta_{\mathrm{S}}. \tag{48}$$

**Lemma 3.** *An upper bound of the overall average throughput for secondary system with an increasing M is given by*

$$\begin{aligned}\eta_{\mathrm{T_S}}^{*} &= \lim_{M\to\infty} \eta_{\mathrm{T_S}} \\ &= \frac{1-O_4}{2(\bar{N}_{\mathrm{C}}+1)}.\end{aligned} \tag{49}$$

## Simulation results

In this section, we show the theoretical and simulation results for the throughput of the primary and secondary systems in the proposed spectrum sharing protocol. The theoretical results are according to the previous analysis, and the simulation results are according to the simulated transmission cases. For ease of exposition, as shown in Figure 1, we assume that the distance is the normalized distance, which is done with respect to the distance between PT and PR, i.e., $d_0 = 1$, $d_{ki} = 0.5$ $(k = 1, 2)$, $d_4 = 0.5$, and the path-loss exponent $\nu = 4$. We let the target rates $R_{\mathrm{p}} = R_{\mathrm{s}} = 1$ and the transmit powers $P_{\mathrm{p}} = P_{\mathrm{s}}$. We use markers to denote the simulation results and lines to denote the analytical results.

Figure 3 shows the throughput for primary system in cooperation mode under different values $M$. When $M = 1$, the results are identical with the spectrum sharing protocol in [29] with one retransmission of the primary system. The upper bound for primary throughput is also plotted when $M \to \infty$. It is apparent that the theoretical results agree well with the simulation results. We can see that the primary throughput in cooperation mode $\eta_{\mathrm{C_P}}$ is always higher than that in the conventional primary system $\eta_{\mathrm{P}}$; thus, credits can be accumulated by the secondary system in cooperation mode. In the low SNR region, the primary throughput in cooperation mode $\eta_{\mathrm{C_P}}$ improves significantly with an increasing number

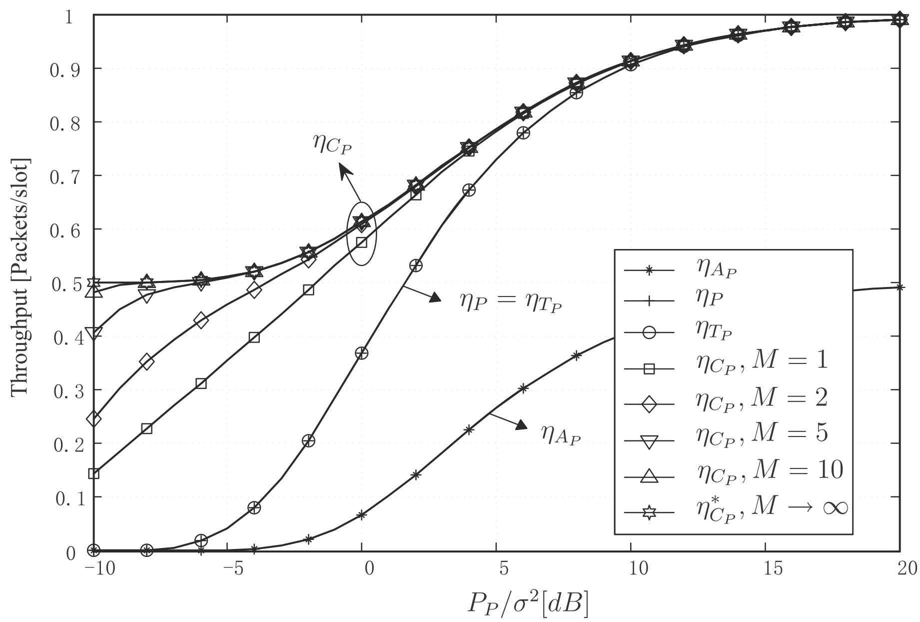


**Figure 3 Theoretical and simulation results for the primary throughput in cooperation mode $\eta_{C_P}$ and access mode $\eta_{T_P}$.**

of $M$ due to the cooperation from the secondary system. On the other hand, in high SNR region, since the outage probability of the direct primary link PT→PR is low, opportunities for cooperation from secondary system decreases, thus increasing $M$ will not improve the performance significantly in the high SNR region. We can also observe that with $M = 10$, the primary throughput under cooperation mode $\eta_{C_P}$ is very close to the upper bound $\eta^*_{C_P}$ when $M \to \infty$.

As shown in Figure 3, the primary system throughput in cooperation mode hits a plateau at about 0.5 in low SNR region and approaches 1 in the high SNR region. This is

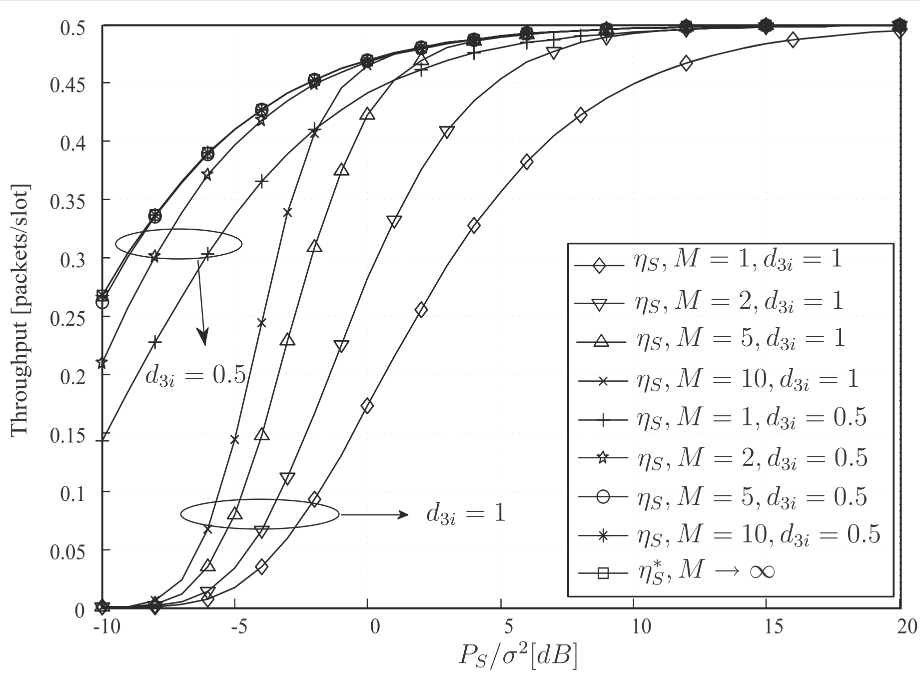


**Figure 4 Theoretical and simulation results of the secondary throughput in access mode $\eta_S$ with different values of $M$.**

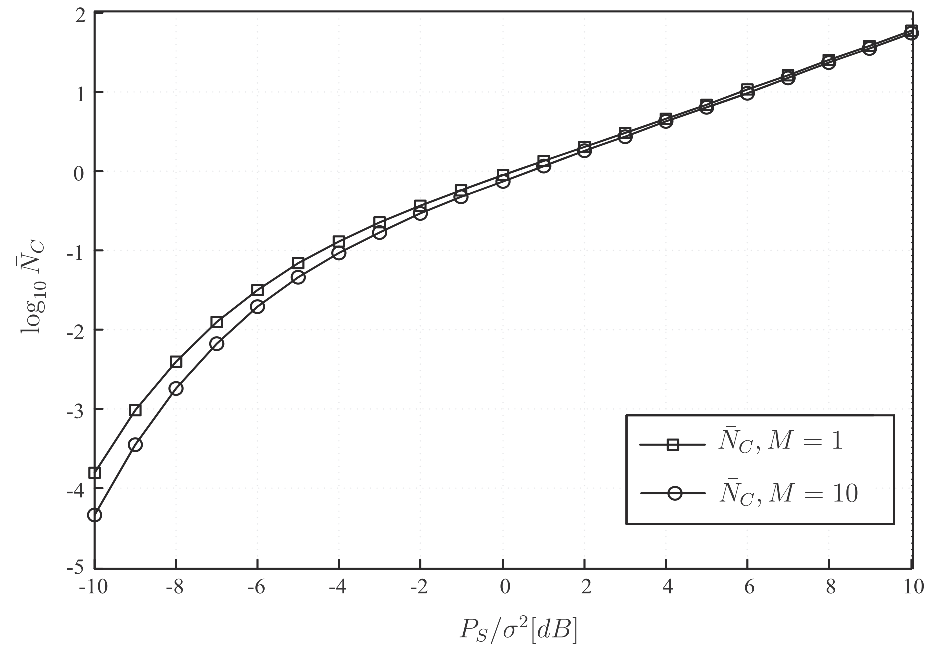


**Figure 5 The ratio between penalties and credits $\log_{10}\bar{N}_{\mathrm{C}}$ under different values of $P_{\mathrm{S}}/\sigma^2$.**

because in the low SNR region, the direct link PT→PR is weak and with $M \to \infty$ secondary transmitters, the probability that the primary packet is successfully relayed by secondary users after two slots approaches 1. On the other hand, in the high SNR region, the direct link PT→PR is so strong that the primary packet is always successfully delivered after the first transmission. Thus, the improvement due to cooperation from secondary users is negligible. It is also observed that the primary throughput in access mode $\eta_{\mathrm{A_P}}$ degrades severely because of the secondary access.

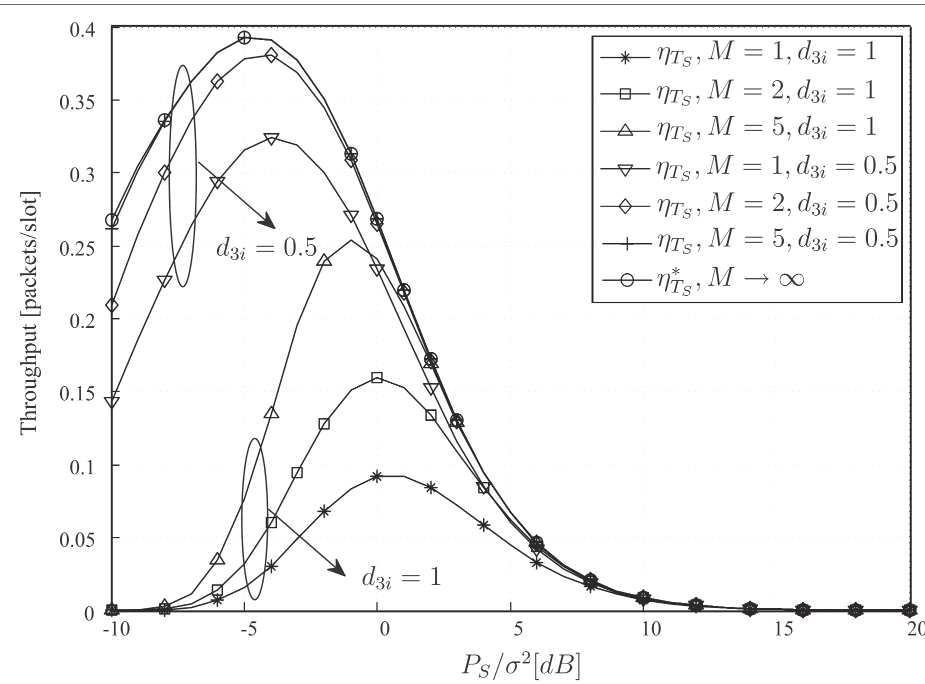


**Figure 6 Theoretical and simulation results of the overall secondary throughput $\eta_{\mathrm{T_S}}$ with different values of $M$.**

However, with the proposed ARQ-based spectrum sharing protocol, it is apparent that the same overall average throughput $\eta_{\mathrm{T_P}} = \eta_{\mathrm{P}}$ is achieved for the primary system compared to the case without relay, while providing secondary spectrum access.

Figure 4 shows the throughput for secondary system in access mode $\eta_{\mathrm{S}}$ under different SNR values $P_{\mathrm{S}}/\sigma^2$. We let $M = 1, 2, 5, 10, \infty$ and $d_{3i} = 1, 0.5$ respectively. It can be observed that the secondary throughput in the access mode increases with an increasing $M$ and a decreasing $d_{3i}$. This is because on one hand, the probability of successfully receiving the secondary packet at SR improves significantly with the increasing $M$. On the other hand, with the decrease of $d_{3i}$, the probability of successful transmission from secondary transmitter to secondary receiver also increases. It is also observed that the secondary throughput in access mode approaches the upper bound $\eta_{\mathrm{S}}^*$, when $d_{3i}$ is decreased from 1 to 0.5 and $M = 10$. A throughput floor of 0.5 appears in the high SNR region for secondary system; this is because both the outage probability of link PT→SR and $\mathrm{ST}_i$ →SR approach 0 in the high SNR region indicate that the probability of successfully decoding the secondary packet in access mode approaches 1. Therefore, in high SNR region, the throughput floor for secondary system in access mode is 0.5 due to the two transmissions.

Figure 5 shows the ratio $\log_{10}(\bar{N}_{\mathrm{C}})$ under different SNR values $P_{\mathrm{S}}/\sigma^2$ in the proposed spectrum sharing protocol. When $\bar{N}_{\mathrm{C}}$ is lower, the access frequency for secondary system, i.e., $1/(\bar{N}_{\mathrm{C}} + 1)$ is higher. From Figure 5 we can observe that in low SNR region, where ratio $\bar{N}_{\mathrm{C}} \rightarrow 0$, the secondary transmitters are able to operate in access mode for most of the time as $1/(\bar{N}_{\mathrm{C}} + 1) \rightarrow 1$, without degrading the primary performance. On the other hand, in high SNR region where $\bar{N}_{\mathrm{C}} \gg 1$, the secondary transmitters have to operate in cooperation mode for most of the time, i.e., $\bar{N}_{\mathrm{C}}/(\bar{N}_{\mathrm{C}} + 1) \rightarrow 1$, before they are allowed to switch to access mode. We also observe that an increase in $M$ will cause a decrease in $\bar{N}_{\mathrm{C}}$. This is because by increasing $M$, the primary throughput gain in cooperation mode increases. Thus, in order to achieve the same primary throughput as in the case without relay, the operating time in access mode can be increased by increasing $M$. However, as shown in Figure 5, when the SNR is high, increasing $M$ will not affect the value of $\bar{N}_{\mathrm{C}}$ significantly, which validates the observation in Figure 3 where the credits due to cooperation from secondary users are negligible in high SNR region.

In Figure 6, we show the overall average throughput for secondary system $\eta_{\mathrm{T_S}}$ under different $P_{\mathrm{S}}/\sigma^2$. We observe that $\eta_{\mathrm{T_S}}$ increases with an increasing $M$. This is because with an increase in $M$, the secondary system collects more credits and hence gains more chances to access the spectrum. Furthermore, with an increasing $M$, a lower outage probability for link $\mathrm{ST}_i$ →SR can be achieved. A peak value of the overall average secondary throughput $\max(\eta_{\mathrm{T_S}})$ for secondary system is achieved in modest SNR values, e.g., around 0 dB for $d_{3i} = 1$ and around −5 dB for $d_{3i} = 0.5$. This is because in the low SNR region, although ST is able to operate for a higher fraction of time $1/(\bar{N}_{\mathrm{C}} + 1)$ in access mode, the corresponding $\eta_{\mathrm{S}}$ is small. On the other hand, in high SNR region, although a higher secondary throughput $\eta_{\mathrm{S}}$ is achieved in access mode, the secondary system has to spend most of the time in cooperation mode. When the distance of $\mathrm{ST}_i$ →SR decreases, the corresponding $\max(\eta_{\mathrm{T_S}})$ occurs in the lower SNR region. This is because with smaller $d_{3i}$, the required SNR to achieve the same $\eta_{\mathrm{S}}$ is lower. At the same time, the access fraction $1/(\bar{N}_{\mathrm{C}}+1)$ is larger in lower SNR region than that in higher SNR.

## Conclusions

We presented an ARQ-based spectrum sharing protocol to achieve spectrum access for multiple secondary transmitters coexisting with a primary system. Upon establishing a credit system, the secondary transmitters alternate between relaying for the primary system and accessing the spectrum for their own use. Credits can be accumulated by secondary transmitters in cooperation mode, which in return allow the secondary system to gain spectrum access in access mode. Our results show that the proposed protocol can achieve secondary spectrum access without degrading the performance of the primary system compared to the conventional system without relays. Furthermore, the throughput for secondary system improves as the number of secondary transmitters increases.

#### Competing interests

The authors declare that they have no competing interests.

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