Cooperative Relay Techniques for Cognitive Radio Systems: Spectrum Sensing and Secondary User Transmissions

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ABSTRACT

Cognitive radio is a promising technology that enables an unlicensed user (also known as a cognitive user) to identify the white space of a licensed spectrum band (called a spectrum hole) and utilize the detected spectrum hole for its data transmissions. To design a reliable and efficient cognitive radio system, there are two fundamental issues: to devise an accurate and robust spectrum sensing algorithm to detect spectrum holes as accurately as possible; and to design a secondary user transmission mechanism for the cognitive user to utilize the detected spectrum holes as efficiently as possible. This article investigates and shows that cooperative relay technology can significantly benefit the above-mentioned two issues, spectrum sensing and secondary transmissions. We summarize existing research about the application of cooperative relays for spectrum sensing (referred to as the cooperative sensing) and address the related potential challenges. We discuss the use of cooperative relays for the secondary transmissions with a primary user's quality-of-service (QoS) constraint, for which a diversity-multiplexing trade-off is developed. In addition, this article shows a trade-off design of cognitive transmissions with cooperative relays by jointly considering the spectrum sensing and secondary transmissions in cognitive radio networks.

INTRODUCTION

Cognitive radio is emerging as a promising technology for future radio networks [1, 2], which enables an unlicensed cognitive user to recognize (by spectrum sensing) and access a spectrum hole that is a radio frequency band licensed to a primary user but not used by that user. In [3], code-division multiple access (CDMA) has been investigated for spectrum sharing between two heterogeneous systems (i.e., a cellular network and a microwave network) through interference suppression. Differing from [3], cognitive radio typically exploits the spectrum sensing to detect spectrum holes for secondary transmissions so that the primary and secondary users can share spectrum resources without harmful interference. In general, ideal spectrum sensing (without miss detection and false alarm) cannot be realized in practice and thus mutual interference between the primary and cognitive users exists, which severely impairs and limits the secondary transmission performance under a target primary quality of service (QoS) requirement, especially with a strict primary QoS constraint [4]. In order to achieve a reliable cognitive radio system with high data rates, it requires both a robust spectrum sensing algorithm and an efficient secondary transmission mechanism so as to detect and utilize the spectrum holes in the most efficient way. To that end, cooperative relay technology is considered as an effective method to improve the performance of both spectrum sensing and secondary transmissions.

The spectrum sensing with cooperative relays (also known as cooperative sensing) has been studied to combat wireless fading effects [5–8]. As is known, each cooperative sensing process requires two essential phases: the phase of the primary user's signal detection by cognitive users and the phase of the initial detection result reporting to a fusion center, referred to as detection and reporting phases, respectively. In [5] and [6], a dedicated channel is considered for reporting the initial detection results from cognitive users to the fusion center in order to avoid interfering with the primary user. However, this approach requires extra spectrum resources and involves complex networking/signaling issue due to the dedicated channel resource management.

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Therefore, in [7, 8], we study a selective-relay-based cooperative sensing (SRCS) scheme without a dedicated reporting channel and examine its receiver operating characteristics (ROC) performance by jointly considering the detection and reporting phases. It is shown in [7] that the SRCS scheme can save dedicated reporting channel resources without sacrificing ROC performance as compared to the conventional approach [5]. Moreover, we show that the cooperative sensing performance can be further optimized through a trade-off design in determining the time durations for the detection and reporting phases.

Cooperative relay technology has been studied extensively for traditional wireless networks [9]. It, however, faces an additional challenging issue in cognitive radio networks, i.e., mutual interference between the primary and cognitive users. Specifically, although a spectrum sensing module is utilized in cognitive radio, it is not practical to achieve ideal spectrum sensing without any miss detection and false alarm. This would introduce mutual interference between the primary and cognitive users. In [4], we study the use of cooperative relays for secondary transmissions and illustrate that, given a primary outage probability requirement, the mutual interference causes an outage probability floor for secondary transmissions in high signal-to-noise ratio (SNR) regions. Using the outage probability floor as a performance metric, we generalize the traditional diversity gain definition and show that the full diversity is still achieved for secondary transmissions with a target primary outage probability requirement. In addition, we provide a generalized multiplexing gain definition in [10] and develop the diversity-multiplexing trade-off of secondary transmissions with a primary QoS constraint.

A reliable cognitive radio system with high data rates is achievable by using cooperative relays for both the spectrum sensing and secondary transmissions. However, the two individual designs of spectrum sensing and secondary transmissions cannot be optimized separately, since they affect each other [11, 12]. For example, when an available spectrum hole is not detected by spectrum sensing during a certain observation window, the spectrum hole utilization would decrease. To alleviate this issue, we may increase the observation time for the spectrum sensing phase, which, however, comes at the cost of degradation in secondary transmission performance since less time is now available for the secondary transmission phase. In [12], we investigate the sensing and transmission trade-off in a multiple-relay cognitive radio network and show that a significant performance improvement is obtained by using cooperative relays in terms of the spectrum hole utilization.

The rest of this article is organized as follows. We describe related cooperative sensing work with a dedicated channel for reporting initial detection results to a fusion center. We also propose an alternative SRCS framework without the dedicated reporting channel and show its ROC performance comparison with the conventional cooperative sensing (with a dedicated reporting channel). We investigate the use of cooperative relays for secondary transmissions with a primary QoS constraint and illustrate the diversity-multiplexing trade-off. Next, we provide a trade-off design between the spectrum sensing and secondary transmissions in multiple-relay cognitive radio networks. Finally, we make concluding remarks.

Cooperative Relays for Spectrum Sensing

Spectrum sensing is regarded as a mandatory feature in cognitive radio networks [2], for which three typical signal detection approaches are available: energy detection, matched filter detection, and feature detection. These detectors work well in Gaussian noise scenarios, which, however, are not appropriate to be directly utilized in wireless fading environments. To that end, cooperative sensing strategies have been studied to combat the wireless fading in [5] and [6], where multiple cognitive users (CUs) independently detect the licensed primary channel using a certain detector (e.g., energy detector) and report their initial detection results to a fusion center (FC).

Typically, each cooperative sensing process consists of two essential phases:

- Detection phase, in which all CUs attempt to detect the presence of a primary user (PU) within a certain time duration (called *signal detection overhead*)
- Reporting phase, in which the initial detection results are forwarded to the FC over the remaining time

A joint detection and reporting analysis is essential to optimize the cooperative sensing performance, since the two phases affect each other and cannot be optimized in isolation. Although the initial detection results contain only a few information bits in an information-theoretical sense, CUs scan the licensed channel periodically and have a non-negligible transmission rate of initial detection results, which would lead to transmission errors in the reporting phase considering the noise and fading effects. This may affect the final fusion result at the FC and degrade the overall spectrum sensing performance. While increasing the time period for the reporting phase can improve the reliability of the initial detection result transmission, it comes at the expense of a reduction in individual detection performance since less time is now available for the detection phase. It would also degrade the overall spectrum sensing performance at the FC.

In addition, when CUs forward their initial detection results to the FC in the reporting phase, they may interfere with the primary user. To avoid such interference, previous research [5, 6] assumed that there is a dedicated channel for reporting the initial detection results, which, however, requires extra channel resources. To that end, we propose a selective-relay based cooperative sensing (SRCS) scheme in [7] and [8] to mitigate the interference from CUs to PU in the reporting phase without a dedicated channel, where each CU forwards its initial detection

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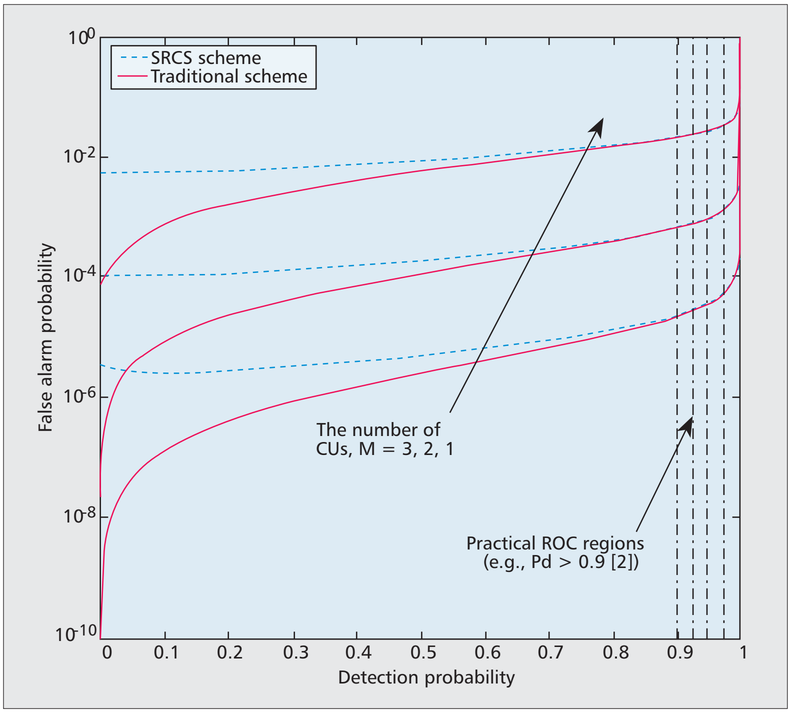

Figure 1. *The false alarm probability vs. detection probability of the traditional cooperative sensing and the SRCS schemes for different number of CUs.*

result in a selective manner depending on if the absence of PU is detected or not. Specifically, if the ith CU (denoted CU_i) detects the absence of PU in its detection phase, it transmits a cyclic redundancy check (CRC)-encoded indicator signal to the FC over the ith orthogonal subchannel of the primary channel, instead of a dedicated channel. Otherwise, nothing is transmitted from CU_i to avoid interfering with PU. At the FC side, if the CRC checking is successful over i-th orthogonal sub-channel, FC considers the absence of PU as the initial result detected by CU_i; otherwise, it considers the presence of PU as the CU_i's initial detection result. Accordingly, in the SRCS scheme, a CU may interfere with PU only if it fails to detect the presence of PU given that PU is active. As discussed in [7], this interference is controllable and can be reduced to satisfy a given primary QoS requirement.

In Fig. 1, we show the ROC performance curves of the traditional cooperative sensing [5] and the SRCS [7] schemes with a primary signal-to-noise ratio of 5dB considering a logic "AND" fusion rule, where the three ROC curve pairs correspond to the different number of CUs, M = 1, 2 and 3, respectively. From Fig. 1, one can observe that in the low detection probability regions, the false alarm probabilities of the SRCS scheme are larger than these of the traditional scheme. However, in higher detection probability regions, it is shown from Fig. 1 that ROC performance of the SRCS scheme is nearly identical to that of the traditional scheme. Notice that practical cognitive radio systems require the detection probability to be above a relatively large value (e.g., at least 0.9 [2]) for the primary user protection. In this sense, the SRCS scheme saves the dedicated reporting channel resources without sacrificing ROC performance as compared to the traditional cooperative sensing.

Figure 2 illustrates the false alarm probability versus signal detection overhead of the SRCS scheme for different number of CUs, M = 1, 2, and 3. From Fig. 2, one can see that an optimal signal detection overhead exists to minimize the false alarm probability under a target detection probability 0.99, i.e., a minimum false alarm probability can be achieved through an optimal allocation of the time durations between the detection and reporting phases. As shown in Fig. 2, the optimal signal detection overhead value decreases with an increasing number of CUs. This is due to the fact that, as the number of CUs increases, each CU is allocated with less bandwidth resources for its initial detection result reporting and thus a longer time duration is needed in the reporting phase, resulting in the decrease of optimal signal detection overhead.

Cooperative Relays for Secondary Transmissions with a Primary QoS Constraint

In this section, we discuss the application of cooperative relays for secondary data transmissions with a primary QoS constraint. As mentioned, ideal spectrum sensing without any miss detection and false alarm is not achievable in practice. This introduces the mutual interference between the primary and cognitive users, resulting in performance floor (e.g., outage probability floor) for the secondary transmissions in high SNR regions with a primary QoS constraint. In the following, we show that cooperative relays can significantly improve the secondary transmission performance without affecting the primary QoS.

Figure 3 shows the coexistence of a primary network with a cognitive radio network, where a primary source (PS) may send data to a primary destination (PD). Meanwhile, in the cognitive radio network, a cognitive source (CS) first detects the activity (presence or absence) of PS in search of a spectrum hole. Given a spectrum hole detected, CS starts its data transmissions to a cognitive destination (CD). We consider that multiple cognitive relays (CRs) are available to assist the secondary data transmissions. Generally speaking, there are two basic relaying protocols, amplify-and-forward (AF) and decode-and-forward (DF), and the latter protocol is considered in this article.

Given multiple CRs available to assist a CS's data transmissions, a straightforward way is to allow all the relays to participate in forwarding the CS's signal to the CD. Although this approach can achieve full diversity gain, it comes at the expense of a reduction in multiplexing gain, since the multiple relays shall transmit on orthogonal channels to avoid interfering with each other. To overcome this issue, an alternative protocol, called the best relay selection, has been studied in cognitive radio networks [4], where only the "best" cognitive relay is selected to forward the CS's signal; thus, only two channels (i.e., the best relay link and direct link) are required regardless of the number of cognitive relays. It has been shown that the best-relay selection protocol can still achieve the full diversity in cognitive radio with a primary QoS constraint [4].

Although the best relay transmission achieves the full diversity, one-half of the multiplexing gain is sacrificed since two orthogonal channels are required. In contrast, the non-relay direct transmission inherits the full multiplexing but without any diversity gain. In [10], we explore a selective best relay cooperation framework by jointly considering the best-relay transmission mode and non-relay direct transmission mode. We examine two specific selective best relay cooperation schemes with and without an acknowledgment (ACK) from the cognitive destination with regard to success or not in decoding, which are called ACK- and non-ACK-based selective best relay cooperation, respectively.

For the non-ACK-based selective best relay cooperation, CD does not acknowledge whether or not it decodes successfully, and only the CRs' outcomes of decoding CS's signal are considered in determining a selective relaying strategy. Specifically, CS first broadcasts a data message to CD and all CRs, and those CRs that can correctly decode CS's signal constitute a so-called decoding set. Then, if the decoding set is not empty, the best cognitive relay among the decoding set is chosen to forward its decoded result to CD. If the decoding set is empty, let CS transmit its subsequent new message which is after the message transmitted earlier.

Differing from the non-ACK scheme, ACK-based selective best relay cooperation allows CD to transmit an ACK to inform CS and all CRs whether it successfully decodes CS's signal or not. To be specific, if CD succeeds in decoding its received signal directly from CS, it broadcasts an ACK signal to CS and CRs so that a new data message would be scheduled for transmission at CS, instead of repeating the previous message by a cognitive relay. Otherwise, in the case of CD failing to decode CS's signal, the remaining process of the ACK-based selective best relay cooperation is same as that of the non-ACK-based scheme.

Figure 4 compares the diversity-multiplexing trade-offs of non-cooperation, and non-ACK and ACK-based selective best relay cooperation schemes, where M represents the number of CRs. One can observe from Fig. 4 that, as the multiplexing gain approaches zero, the maximum diversity gains of the non-ACK and ACK-based selective cooperation schemes with $M = 1$, 2, and 4 are equal to 2, 3, and 5, respectively, showing the full diversity achieved by both the non-ACK and ACK schemes. On the other hand, as the diversity gain decreases to zero, a multiplexing gain of only 1/2 is achieved by the non-ACK-based cooperation scheme regardless of the number of CRs. For the ACK-based cooperation scheme, as the number of CRs increases from $M = 1$ to 4, the maximum multiplexing gains decrease from 2/3 to 5/9, which are always larger than 1/2, showing its advantage over the non-ACK-based scheme [10].

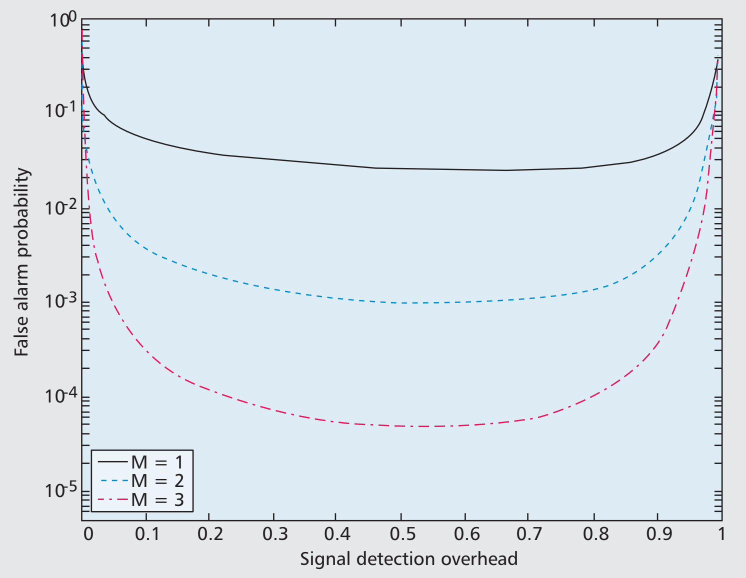

Figure 2. *The false alarm probability vs. signal detection overhead of the SRCS scheme for different number of CUs,* M*, with a target detection probability of 0.99.*

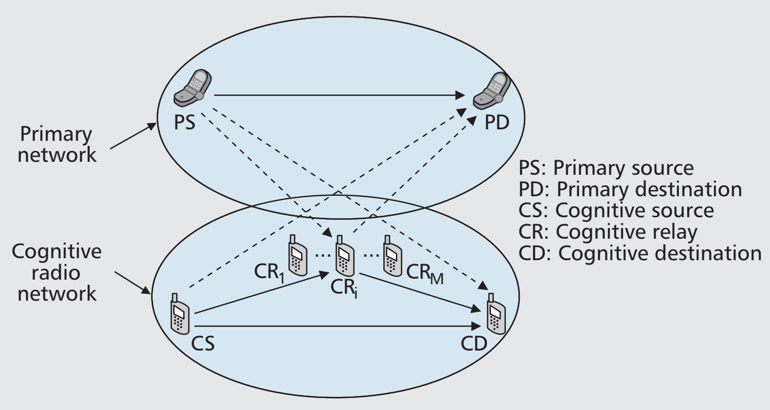

Figure 3. *A cognitive radio network with multiple cognitive relays.*

Trade-off between Spectrum Sensing and Secondary Transmissions

In this section, we study a trade-off design of the cognitive transmissions by jointly considering the spectrum sensing and secondary transmissions. As discussed in [8] and [12], the two individual phases cannot be optimized separately, since they affect each other. In [12], we have explored the cognitive transmissions with multiple relays that are utilized for both the spectrum sensing and secondary transmissions. As shown in Fig. 5, each cognitive transmission process consists of two phases (i.e., the spectrum sensing and secondary transmission phases), where the parameter α is referred to as spectrum sensing overhead, which is to be adjusted to optimize the cognitive transmission performance [12].

Figure 5 shows that, in the spectrum sensing phase, there are two subphases: the primary user detection and initial detection result reporting

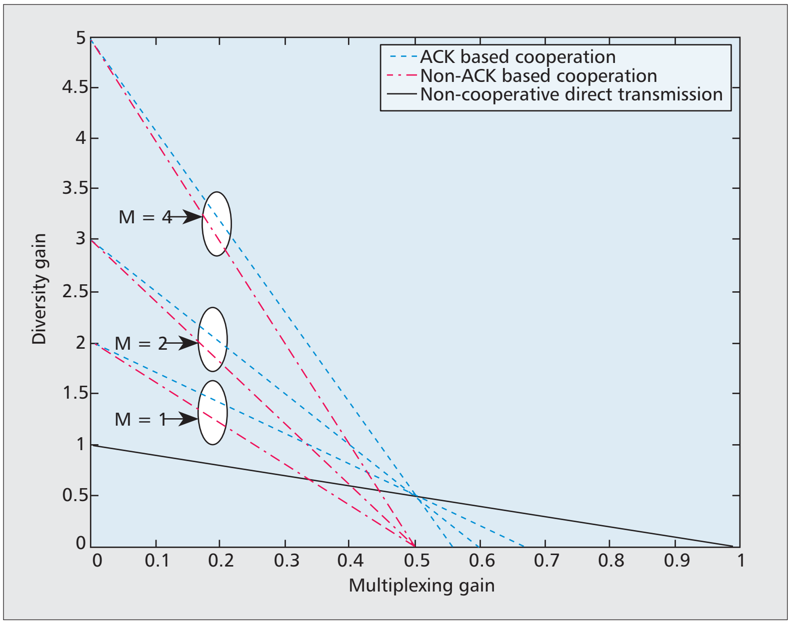

Figure 4. *Diversity-multiplexing trade-offs of the non-cooperative transmission, and the non-ACK and ACK-based selective best relay cooperation schemes with different numbers of cognitive relays.*

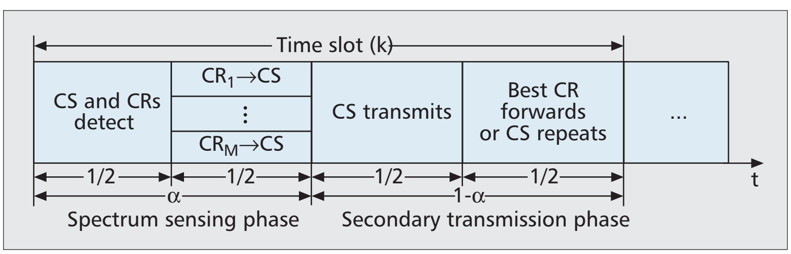

Figure 5. *Time slot structure of the cognitive transmissions with multiple relays.*

phases. To be specific, in the detection subphase, a cognitive source and all cognitive relays independently detect the presence or absence of the primary user. In the subsequent reporting subphase, all CRs forward their initial detection results to CS for fusion. Here, two fusion strategies are considered: fixed fusion and selective fusion, which lead to fixed fusion spectrum sensing (FFSS) and selective fusion spectrum sensing (SFSS) schemes, respectively. In the FFSS scheme, CRs transmit their initial detection results to CS without using any forward error detection code, and CS decodes the received initial detection results from CRs and combines all the decoded outcomes. In contrast, the SFSS scheme employs an additional forward error detection code (such as cyclic redundancy check code) at CRs to encode their initial detection results. The encoded signals are transmitted to CS, which decodes the received signals and combines the successfully decoded outcomes only; that is, only the successfully received initial detection results are selected and used for fusion.

As shown in Fig. 5, the secondary transmission phase also consists of two subphases. Given a spectrum hole detected earlier in the spectrum sensing phase, CS starts transmitting its data to CD and CRs in the first secondary transmission subphase. Then, in the subsequent sub-hase, a best relay data transmission (BRDT) strategy is used for the secondary transmission. Specifically, all CRs attempt to decode their received signals (from CS), and those CRs that decode successfully constitute a decoding set. If the decoding set is not empty, we choose the best relay within the decoding set to forward its decoded result to CD. If the decoding set is empty (i.e., no relay is able to decode the CS's signal successfully), let CS repeat the transmission of the original signal to CD through its direct link. Finally, CD combines the two copies of the received signals using a certain combining method and gives an estimation of the original signal.

In Fig. 6, we show the spectrum hole utilization vs. spectrum sensing overhead of the FFSS-BRDT and SFSS-BRDT schemes for different data rates R, R = 1 b/s/Hz and 1.5 b/s/Hz. Note that the spectrum hole utilization is used to quantify the percentage of spectrum holes utilized for secondary data transmissions without outage events. Figure 6 illustrates that an optimal spectrum sensing overhead exists to maximize the spectrum hole utilization for both the FFSS-BRDT and SFSS-BRDT schemes. Hence, a joint analysis of the spectrum sensing and secondary transmission phases is essential to optimize the overall performance of cognitive radio transmissions. One can also observe from Fig. 6 that, no matter which scheme (FFSS-BRDT or SFSS-BRDT) is used, the optimal spectrum sensing overhead corresponding to R = 1.5 b/s/Hz is smaller than that for R = 1 b/s/Hz. This is because, as the data rate increases, the secondary transmission phase should be allocated a relatively longer time duration, which results in less time available for the spectrum sensing phase. In addition, it is shown from Fig. 6 that the spectrum hole utilization of the SFSS-BRDT scheme is always higher than that of the FFSS-BRDT scheme across the whole spectrum sensing overhead regions.

Conclusions

This article describes the application of cooperative relays for both the spectrum sensing and secondary transmissions to achieve a reliable and efficient cognitive radio system. We present a selective-relay-based cooperative sensing scheme without a dedicated channel to report initial detection results for fusion and show its advantage over traditional cooperative sensing (with a dedicated reporting channel). We also discuss the use of cooperative relays for the secondary transmissions with a primary QoS constraint and provide a diversity-multiplexing trade-off evaluation. In addition, it is shown that the cognitive radio transmission performance can be optimized in terms of the spectrum hole utilization through a joint analysis of the spectrum sensing and secondary transmissions.

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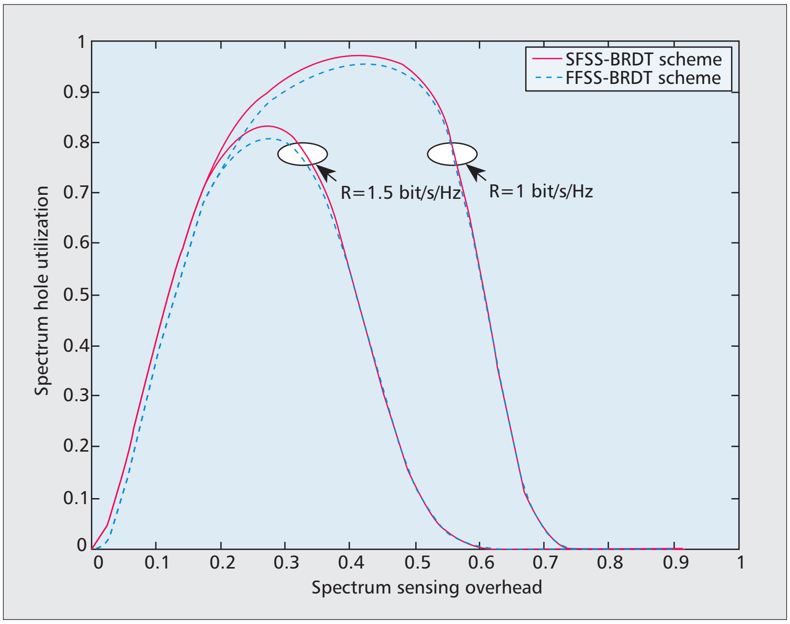

Figure 6. *The spectrum hole utilization vs. spectrum sensing overhead of the FFSS-BRDT and SFSS-BRDT schemes with the number of cognitive relays* M = *4.*

BIOGRAPHIES

YULONG ZOU received his B.Eng. degree in information engineering from Nanjing University of Posts and Telecommunications (NUPT), China, in 2006. He is currently working toward his dual Ph.D. degree at the Institute of Signal Processing and Transmission of NUPT, and the Electrical and Computer Engineering Department of Stevens Institute of Technology (SIT), New Jersey. His research interests span a wide range of topics in wireless communications and signal processing, including cooperative communications, space-time coding, network coding, and cognitive radio. Recently, he has been working on cooperative relay techniques in cognitive radio networks, opportunistic distributed space-time coding in cooperative wireless networks, and full-diversity high-rate network coding for cellular systems (e.g., LTE/IMT-advanced and beyond).

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