Cognitive AF Relay Schemes for Uplink Transmission in Macrocellular Networks

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***Abstract*—Cognitive radio has been proposed to improve the spectrum utilization by allowing the unlicensed secondary users (SUs) to access the spectrum resources licensed to the primary users (PUs) opportunistically. However, the cognitive radio has rarely been employed to enhance the system performance of the licensed PUs that endure spectrum scarcity. To improve the outage-probability quality-of-service (QoS) of the mobile station (MS) in macrocellular networks, we propose two Cognitive Amplify-and-forward Relay (CAR) schemes in this paper. In our proposed CAR schemes, the MS and relay utilize both the licensed spectrum band (LSB) provided to the macrocellular network and the opportunistic spectrum band (OSB) discovered by the base stations. Simulation results show that compared with the conventional transmission schemes without cognitive relay, our proposals can effectively improve the outage performance of MS in macrocellular networks by exploiting both the space diversity and spectrum diversity.**

I. Introduction

The rapid development of wireless communications systems brings challenges to the spectrum regulators on allocating the precious wireless spectrum resources to new services. However, field measurements show that most of the licensed spectrum resources are under-utilized [1]. To solve such a contradiction, cognitive radio has been proposed to access the licensed spectrum bands opportunistically [2].

One of the basic requirements for the cognitive radio system is that it should not cause harmful interference to the licensed primary users (PUs) [3]. To implement cognitive communications connecting end terminals, there are usually two major approaches. One is opportunistic spectrum access based on spectrum sensing [4][5], while the other is dynamic spectrum sharing without spectrum sensing [6][7]. The former requires each cognitive terminal to be equipped with one additional radio for spectrum sensing. The latter requires the unlicensed secondary users (SUs) to get the knowledge on the positions of PU transceivers and the channel gain between them, which however is unrealistic for the inactive PU receivers, e.g., the television receivers [8].

Abundant efforts on the cognitive radio system based on dynamic spectrum access and spectrum sensing have been reported in the literature. These efforts aim at realize cognitive communication between end terminals that have no licensed spectrum. In [9], the authors surveyed the current achievements in sensing the availabilities of PU spectrum bands. Authors in [10] proposed an efficient cognitive-radio enabled multi-channel medium access control (MAC) protocol that enables the SUs to utilize the spectrum opportunities effectively while avoiding collisions. To manage the spectrum opportunities, authors in [11] advocated to establish a spectrum secondary market for SUs to dynamically trade their channel holdings or spectrum opportunities obtained from the PUs.

Cognitive relay protocols have been introduced to improve the system performance of SUs by exploiting space diversity. In [12], the authors proposed a cooperative spectrum sensing scheme based on the amplify-and-forward (AF) protocol to improve the spectrum sensing performance of the SU systems. The authors in [13] introduced cooperative communication by using cognitive relay protocols between SUs. Conventionally, the mobile station (MS) in macrocellular networks has licensed spectrum band but is sensitive to transmission outage. The outage performance of a terminal can be improved by using the multi-input-multi-output (MIMO) technology [14]. However, the limited terminal size of MS makes it difficult to implement MIMO between the MS and the base station (BS) over the same frequency band [15]. Authors in [16] proposed a cognitive relay scheme to mitigate the intercell interference in cellular systems, which could be mitigated alternatively through spectrum planning.

To improve the outage performance of the licensed MS in macrocellular networks, we propose and compare two Cognitive AF Relay (CAR) schemes in this paper: CAR based on Selective Transmission (CAR-ST) and CAR based on Equal Weight Combination (CAR-EWC). In our proposed CAR schemes, the MS and relay utilize both its licensed spectrum band (LSB) and the opportunistic spectrum band (OSB) discovered by the base station system (BSS). There are two stages in each relay process. During the first stage, the MS transmits only over the LSB in the CAR-ST scheme, while the MS transmits over both the LSB and OSB in the CAR-EWC scheme. During the second stage, the relay amplifies the signal received over the LSB, and then forwards the amplified signal over both the LSB and OSB in the CAR-ST scheme. In the CAR-EWC scheme, the relay combines the signals received over the LSB and OSB with equal weight, and then the combined signal is amplified and forwarded over both the LSB and OSB. Since our proposals exploits the spectrum diversity and space diversity, they are expected to improve the outage performance of the MS in Macrocellular networks.

The rest of this paper is organized as follows. Section II presents the system model. Section III describes our proposed cognitive AF relay schemes. In Section IV, we analyze the outage performance of our proposed cognitive AF relay schemes. We give simulation results in Section V. Finally, brief conclusions are drawn in Section VI.

II. System Model

We consider a cell in macrocellular networks, as shown in Fig. 1. Within the cell, the source or MS transmits regularly over its LSB with one relay between itself and the destination

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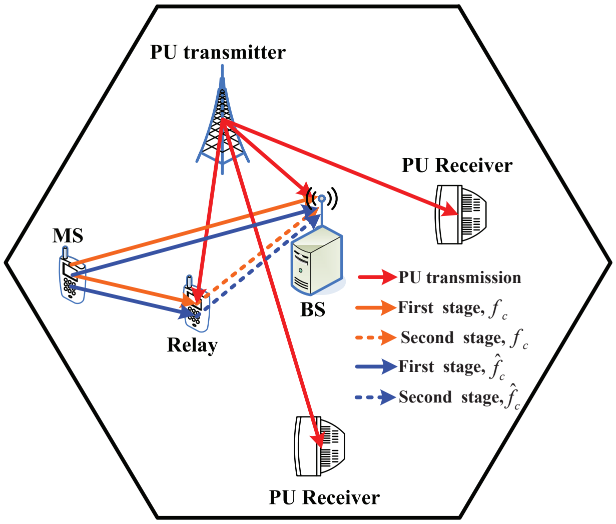

Fig. 1: Cognitive relay in a macrocell, where f_c and $\hat{f}_c$ are the carrier frequencies of the LSB and OSB, respectively.

or BS. To improve the system performance of the MS, the cell opportunistically accesses the OSB licensed to the PU. Therefore, the MS, BS and relay each has to be equipped with two radios that operate over the OSB and LSB, respectively. Without loss of generality, we assume that the MS is within the coverage of the PU transmitter and a specific MS is designated to opportunistically utilize one PU band. Then, the transmission of the MS over the OSB is potentially interfered by the PU transmission.

A. *Spectrum Sensing*

To protect the PU, the MS and relay have to be informed of the available spectrum opportunities before they can transmit over the corresponding OSB. We assume that these spectrum opportunities are provided by the BSS and shared by both the MS and relay through a common control channel. In other words, the MS, relay and BS have the same knowledge on the availabilities of spectrum opportunities.

The BSS gets the spectrum opportunities through spectrum sensing [9]. The sensing performance of the BSS is generally characterized by its probability of detection P_d and probability of false alarm P_f for a given pair of sensitivity and sensing time. It is required that $P_d \geq 0.9$ and $P_f \leq 0.1$ when the average PU signal to noise ratio (SNR) over the OSB is $-20dB$ [3]. We assume that the BSS obtains spectrum opportunities from the digital video broadcasting (DVB) band. Since the macrocellular networks generally have wide coverage and the PU transmitters over a same DVB frequency band transmit simultaneously [8], some BSs may be adjacent to the PU transmitters. Therefore, it is reasonable to assume that the BSS can sense the PU activity with negligible duration.

B. *Cognitive Relay Protocol*

The MS can always transmit over its LSB with carrier frequency f_c. However, to protect the PU, the opportunistic transmission over the OSB with carrier frequency $\hat{f}_c$ is allowed only when the PU transmission is detected to be vacant. The relay transmission protocol between the MS and BS is shown in Fig. 2, which corresponds to the layout shown in Fig. 1. It is assumed the time spent on combination can be neglected.

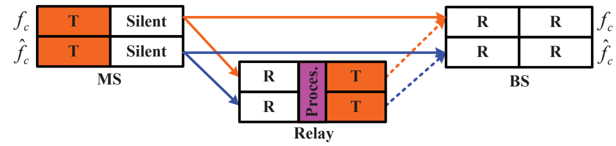

Fig. 2: Cognitive relay transmission protocol where the signals received at the relay are processed (proces.)

As shown in Fig. 2, each frame is divided into two stages. During the first stage, the MS transmits over both its LSB regularly and the OSB opportunistically. At the BS, the signal received over the LSB $y_d[n]$ and OSB $\widehat{y}_d[n]$ are

$$\begin{aligned} y_d[n] &= h_{sd}\bar{x}_s[n] + z_d[n] \\ \widehat{y}_d[n] &= \theta\left(g_{sd}\bar{x}_s[n] + \eta k_{pd} x_p[n] + \widehat{z}_d[n]\right) \end{aligned} \quad (1)$$

where $n = 1, 2, \cdots, L/2$ represent the sample indices in the first half of each frame; h_{sd} and g_{sd} are the channel gains between the MS and BS over the LSB and OSB, respectively; $z_d[n]$ and $\widehat{z}_d[n]$ denote the additive white Gaussian noise (AWGN) at the BS over the LSB and OSB, respectively; $x_p[n]$ is the potential interfering signal from the PU; k_{pd} is the channel gain between the PU transmitter and BS; $\theta \in \{0, 1\}$ is the decision to transmit ($\theta = 1$) or to keep silent ($\theta = 0$) over the OSB; $\eta \in \{0, 1\}$ is the PU state on presence ($\eta = 1$) or absence ($\eta = 0$). Conventionally, the MS transmits its signal $x_s[n]$ with normal power P_s. However, since MS is generally power limited, a power coefficient is utilized in our proposals to constraint the transmission power of the MS, i.e., $\bar{x}_s[n] = (1/\sqrt{2})^{\theta} x_s[n]$. In other words, once the MS decides to transmit over the OSB ($\theta = 1$), it transmits simultaneously over both the LSB and the OSB with power $P_s/2$. Otherwise ($\theta = 0$), it transmits over the LSB with power P_s.

At the same time, the signals received by the relay from the MS over the LSB $y_r[n]$ and OSB $\widehat{y}_r[n]$ can be presented as

$$\begin{aligned} y_r[n] &= h_{sr}\bar{x}_s[n] + z_r[n] \\ \widehat{y}_r[n] &= \theta\left(g_{sr}\bar{x}_s[n] + \eta k_{pr} x_p[n] + \widehat{z}_r[n]\right) \end{aligned} \quad (2)$$

where $n = 1, 2, \cdots, L/2$; h_{sr} and g_{sr} are the channel gains between the MS and relay over the LSB and OSB, respectively; $z_r[n]$ and $\widehat{z}_r[n]$ are the AWGN at the relay over the LSB and OSB, respectively; k_{pr} is the channel gain between the PU transmitter and relay.

During the second stage, the relay amplifies and forwards a combination of the signals received over both the LSB and the OSB. Let $x_r[n]$ and $\widehat{x}_r[n]$ be the signals transmitted at the relay over the LSB and OSB, respectively. Then, the signals received at the BS over the LSB and OSB are

$$\begin{aligned} y_d[n] &= h_{rd} x_r[n] + z_d[n] \\ \widehat{y}_d[n] &= \theta\left(g_{rd}\widehat{x}_r[n] + \eta k_{pd} x_p[n] + \widehat{z}_d[n]\right) \end{aligned} \quad (3)$$

where $n = L/2 + 1, \cdots, L$ represent the sample time indices in the second half or stage of each frame; h_{rd} and g_{rd} are the channel gains between the relay and BS over the LSB and OSB, respectively.

Note that θ in (1)$\sim$(3) is to guarantee that the corresponding end terminal receives over the OSB only when the PU is detected to be absent. Without loss of generality, we assume that all the channels are block faded and independent of each other. Note that we only consider the uplink transmission in this paper, since the downlink transmission is pairwise.

III. Cognitive AF Relay Schemes

Over the OSB, the licensed right of the PU is guaranteed by requiring the macrocellular network to offer an acceptable probability of detection P_d [3]. However, the right and thus the Quality-of-Service (QoS) of the MS over the OSB is not guaranteed by the PU. In other words, over the OSB, the MS can cause acceptable interference to the PU, while the PU may cause unpredictable interference to the MS. In this section, we propose and compare two new CAR schemes to make efficient use of the spectrum opportunities over the OSB. These CAR schemes can exploit the space diversity from spatially distributed terminals and the spectrum diversity by transmitting opportunistically over the OSB.

A. Cognitive AF Relay Based on Selective Transmission

During the first stage of the CAR-ST scheme, the MS only transmits over its LSB, while the transmission over the OSB is forbidden. In other words, regardless of the result of spectrum sensing, θ is forced to be zero, i.e., $\theta = 0$. Therefore, according to (1), the signals received at the BS over the LSB and OSB during the first stage can be derived as

$$\begin{aligned} y_d^{ST}[n] &= h_{sd}x_s[n] + z_d[n] \\ \widehat{y}_d^{ST}[n] &= 0 \end{aligned} \tag{4}$$

where $n = 1, 2, \cdots, L/2$. In (4), the fact that $x_s[n] = \bar{x}_s[n]$ when $\theta = 0$ is utilized. Similarly, according to (2), the signals received at the relay over the LSB and OSB during the first stage can be derived as

$$\begin{aligned} y_r^{ST}[n] &= h_{sr}x_s[n] + z_r[n] \\ \widehat{y}_r^{ST}[n] &= 0 \end{aligned} \tag{5}$$

where $n = 1, 2, \cdots, L/2$. Note that in (4) and (5), the BS and relay receives $x_s[n]$ rather than $\bar{x}_s[n]$ over the LSB, while nothing is received over the OSB. This is mainly because the MS only transmits over its LSB and the transmitted signal is $x_s[n]$ with power P_s rather than $\bar{x}_s[n]$ with power $(1/2)^\theta P_s$.

During the second stage, the signal received over the LSB during the first stage is amplified and forwarded over both the LSB and OSB. The signals to be transmitted over the LSB $x_r[n] = x_r^{ST}[n]$ and OSB $\widehat{x}_r[n] = \widehat{x}_r^{ST}[n]$ are

$$\begin{aligned} x_r^{ST}[n] &= \varphi_1 y_r^{ST}[n - L/2] \\ \widehat{x}_r^{ST}[n] &= \theta\varphi_1 y_r^{ST}[n - L/2] \end{aligned} \tag{6}$$

where $n = 1 + L/2, \cdots, L$ and $\varphi_1 = \sqrt{\frac{P_r}{2^\theta\left(|h_{sr}|^2 P_s + N_r\right)}}$ is the power scaling factor. It can be seen from (6) that the power scaling factor φ_1 imposed on the relay also incorporates the power coefficient $(1/\sqrt{2})^\theta$.

B. Cognitive AF Relay Based on Equal Weight Combination

In the CAR-EWC scheme, the signals received at the relay over both the LSB and OSB are combined with equal weight. The combined signal after EWC can be presented as

$$y_r^{EWC}[n] = y_r[n] + \widehat{y}_r[n] \tag{7}$$

where $n = 1, 2, \cdots, L/2$. By substituting (2) into (7), the combined signal at the relay can be represented as

$$y_r^{EWC}[n] = (h_{sr} + \theta g_{sr})\bar{x}_s[n] + \theta\eta k_{pr}x_p[n] + \theta\widehat{z}_r[n] + z_r[n] \tag{8}$$

where $n = 1, 2, \cdots, L/2$. It can be seen from (8) that when $\theta = 1$ and $\eta = 1$, there exists interference in the combined signal $y_r^{EWC}[n]$, which originates from the PU transmission over the OSB. Note that when $\theta = 1$ and $\eta = 1$, the BSS fails to detect the presence of the PU signal.

Then, the combined signal $y_r^{EWC}[n]$ in (8) is amplified and forwarded simultaneously over both the LSB and OSB by the relay. The signals to be transmitted during the second half of each frame at the relay over the LSB $x_r[n] = x_r^{EWC}[n]$ and over the OSB $\widehat{x}_r[n] = \widehat{x}_r^{EWC}[n]$ are

$$\begin{aligned} x_r^{EWC}[n] &= \varphi_2 y_r^{EWC}[n - L/2] \\ \widehat{x}_r^{EWC}[n] &= \theta\varphi_2 y_r^{EWC}[n - L/2] \end{aligned} \tag{9}$$

where the indices $n = 1 + L/2, \cdots, L$ represent the sample indices; $\varphi_2 = \sqrt{\frac{P_r}{|h_{sr}+\theta g_{sr}|^2 P_s + 2^\theta\left(\theta\eta|k_{pr}|^2 P_p + (1+\theta)N_r\right)}}$ is the power scaling factor. Since there exists interference in (9), the relay amplifies and forwards not only the signal $x_s[n]$ from the MS but also the potential interfering signal $x_p[n]$ from the PU. Note that in (9), the power coefficient $(1/\sqrt{2})^\theta$ imposed on the relay is also included in the power scaling factor φ_3.

It has to be pointed out that in (6) and (9), the parameter θ is to guarantee that the relay transmits only when the PU is detected to be absent. It can be seen from (6) that the CAR-ST scheme does not amplifies and forwards the potential interference, while it can also be observed from (9) that the CAR-EWC scheme amplifies and forwards the potential interference over both the LSB and OSB.

IV. Outage Performance

Although the MS transmits regularly over its LSB, it transmits over the OSB only when the PU is detected to be absent. Therefore, the following four cases should be considered in the performance analyses. 1) False Alarm (FA): The PU is absent, but the BSS falsely claims the presence of the PU. 2) Correct Detection (CD): The PU is present and the BSS correctly detects its presence. 3) Correct Sensing (CS): the PU is absent and the BSS correctly senses the spectrum opportunity. 4) Miss Detection (MD): The PU is present, but the BSS fails or misses to detect its presence.

Without loss of generality, we assume that the MS and relay have the same transmission power, i.e., $P_s = P_r = P$. Moreover, we assume that the power of AWGN at the relay is the same as that at the BS, i.e., $N_r = N_d = N$. For the convenience of discussion, let $\gamma_s = P/N$ and $\gamma_p = P_p/N$ be the average signal to noise ratio (SNR) and interference to noise ratio (INR), respectively. To protect the licensed PU over the OSB, the probability of detection should be not lower than a predefined threshold [3].

A. Cognitive AF Relay Based on Selective Transmission

By substituting (6) into (3), the signal received by the BS during the second stage over the LSB and OSB can be respectively presented by

$$\begin{aligned} y_d[n] &= h_{rd}\varphi_1 y_r^{ST}\left[n - \tfrac{L}{2}\right] + z_r[n] \\ \widehat{y}_d[n] &= \theta\left(g_{rd}\varphi_1 y_r^{ST}\left[n - \tfrac{L}{2}\right] + \eta k_{pd}x_p[n] + \widehat{z}_d[n]\right) \end{aligned} \tag{10}$$

where $n = 1 + L/2, \cdots, L$.

By applying maximum-ratio combining to (4) and (10), the mutual information $I_{ST}(\theta, \eta)$ between the BS and MS can be presented by [17]

$$I_{ST}(\theta, \eta) = \frac{1}{2^\theta}\log\left(1 + \gamma_1^{ST}(\theta, \eta) + \gamma_2^{ST}(\theta, \eta)\right) \tag{11}$$

where $\gamma_1^{ST}(\theta,\eta)$ is the signal to interference-plus-noise ratio (SINR) over the LSB and $\gamma_2^{ST}(\theta,\eta)$ is the SINR over the OSB. They can be presented by

$$\begin{array}{l} \gamma_1^{ST}(\theta,\eta) = |h_{sd}|^2\gamma_s + \frac{|h_{rd}\varphi_1 h_{sr}|^2\gamma_s}{|h_{rd}\varphi_1|^2+1} \\ \gamma_2^{ST}(\theta,\eta) = 0 + \frac{\theta|g_{rd}\varphi_1 h_{sr}|^2\gamma_s}{|\eta k_{pd}|^2\gamma_p+|g_{rd}\varphi_1|^2+1} \end{array} \tag{12}$$

According to (11) and (12), for a desired rate R, the outage probability of the CAR-ST scheme can be derived as

$$P_{out}^{ST} = \left[P_{ST}^{(00)}P_{00} + P_{ST}^{(10)}P_{10}\right]P(H_0) + \left[P_{ST}^{(01)}P_{01} + P_{ST}^{(11)}P_{11}\right]P(H_1) \tag{13}$$

where $P_{00} = P_f$; $P_{ST}^{(00)} = P(I_{ST}(0,0) < R)$ is the outage probability in the case of FA; $P_{10} = 1 - P_f$; $P_{ST}^{(10)} = P(I_{ST}(1,0) < R)$ is the outage probability in the case of CS; $P(H_0)$ is the probability that the PU is absent; $P_{01} = P_d$; $P_{ST}^{(01)} = P(I_{ST}(0,1) < R)$ is the outage probability in the case of CD; $P_{11} = 1 - P_d$; $P_{ST}^{(11)} = P(I_{ST}(1,1) < R)$ is the outage probability in the case of MD; $P(H_1) = 1 - P(H_0)$ is the probability that the PU is present.

B. Cognitive AF Relay Based on Equal Weight Combination

By substituting (9) into (3), the signals received at the BS during the second half of each frame over the LSB and OSB can be respectively presented as

$$\begin{array}{l} y_d[n] = h_{rd}\varphi_2 y_r^{EWC}\left[n - \frac{L}{2}\right] + z_d[n] \\ \widehat{y}_d[n] = \theta\left(g_{rd}\varphi_2 y_r^{EWC}\left[n - \frac{L}{2}\right] + \eta k_{pd}x_p[n] + \widehat{z}_d[n]\right) \end{array} \tag{14}$$

where $n = 1 + L/2, \cdots, L$.

By applying maximum-ratio combining to (1) and (14), the mutual information between the MS and BS can be derived as [17]

$$I_{EWC}(\theta,\eta) = \frac{1}{2^\theta}\log\left(1 + \gamma_{EWC}^1(\theta,\eta) + \gamma_{EWC}^2(\theta,\eta)\right) \tag{15}$$

where $\gamma_{EWC}^1(\theta,\eta)$ is the SINR over the LSB and $\gamma_{EWC}^2(\theta,\eta)$ is the SINR over the OSB. They can be presented by

$$\begin{array}{l} \gamma_1^{EWC}(\theta,\eta) = \frac{1}{2^\theta}|h_{sd}|^2\gamma_s + \frac{|h_{rd}\varphi_2(h_{sr}+\theta g_{sr})|^2\gamma_s}{\left(\Sigma_1^{EWC}+(\theta+1)|h_{rd}\varphi_2|^2+1\right)} \\ \gamma_2^{EWC}(\theta,\eta) = \frac{\theta|g_{sd}|^2\gamma_s}{2^\theta\left(\eta|k_{pd}|^2\gamma_p+1\right)} + \frac{\theta|g_{rd}\varphi_2(h_{sr}+g_{sr})|^2\gamma_s}{2^\theta\left(\Sigma_2^{EWC}+2|g_{rd}\varphi_2|^2+1\right)} \end{array} \tag{16}$$

where for presentation purpose, $\Sigma_1^{EWC} = \theta\eta|h_{rd}\varphi_2 k_{pr}|^2\gamma_p$ and $\Sigma_2^{EWC} = \eta\left(|g_{rd}\varphi_2 k_{pr}|^2 + |k_{pd}|^2\right)\gamma_p$.

According to (15) and (16), for a desired rate R, the outage probability of the CAR-EWC scheme can be derived as

$$P_{out}^{EWC} = \left[P_{EWC}^{(00)}P_{00} + P_{EWC}^{(10)}P_{10}\right]P(H_0) + \left[P_{EWC}^{(01)}P_{01} + P_{EWC}^{(11)}P_{11}\right]P(H_1) \tag{17}$$

where $P_{EWC}^{(00)} = P(I_{EWC}(0,0) < R)$ and $P_{EWC}^{(10)} = P(I_{EWC}(1,0) < R)$ are the outage probabilities in the cases of FA and CS, respectively; $P_{EWC}^{(01)} = P(I_{EWC}(0,1) < R)$ and $P_{EWC}^{(11)} = P(I_{EWC}(1,1) < R)$ are the outage probabilities in the cases of CD and MD, respectively.

V. SIMULATION RESULTS

In this section, we carry out Monte Carlo simulations to show the outage performance of our proposed CAR schemes. Without loss of generality, we assume that all the channels experience independent and identically distributed Rayleigh fading. We also assume that the BSS is capable of realizing a given pair of probability of detection $P_d = 0.9$ and probability of false alarm $P_f = 0.1$ for the INR range considered [9].

We assume that the PU transmits based on the DVB-T signaling [8]. The probability that the PU is present and absent is assumed to be $P(H_1) = 0.1$ and $P(H_0) = 1 - P(H_1) = 0.9$, respectively [3]. In the simulations, we let $R = 1$. For the convenience of comparison, we also give the outage performance of the direct transmission scheme and the AF relay scheme without cognitive relay transmission, which are presented in [17]. Note that the outage performance of the direct transmission scheme or AF relay scheme without cognitive relay transmission is irrelevant to the INR, since these two schemes only transmit over the LSB.

Fig. 3 compares the outage performance of four different schemes when the INR is $\gamma_p = 0dB$. It can be seen that the outage performance of each scheme improves with the increase of SNR. It can also be observed that compared with the direct transmission scheme and AF relay scheme, the outage performance of the MS is improved by using our proposals. When $\gamma_p = 0dB$, the CAR-EWC scheme generally outperforms the CAR-ST scheme. This is mainly because compared with the CAR-EWC scheme, the CAR-ST lost the spectrum diversity in the first stage over the OSB.

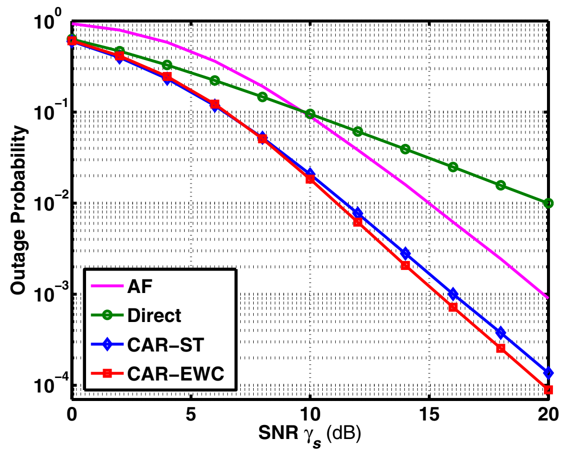

Fig. 3: Outage probabilities when the INR is $\gamma_p = 0dB$.

Fig. 4 compares the outage performance of four different schemes when the SNR is $\gamma_s = 10dB$. It can be seen that the outage probability of each CAR scheme increases with the increase of the INR. It can also be observed that when the INR is larger than about $6dB$, the CAR-EWC scheme performs worse than the CAR-ST scheme. This complies with the fact that the CAR-EWC scheme amplifies and forwards the potential interference from the PU, while the CAR-ST scheme does not. In addition, the outage probability of each CAR scheme increases drastically when the INR γ_p is around $10dB$, which means that the impacts of interference on the outage performance become significant when the INR is comparable with the SNR.

Fig. 5 compares the outage performance of four different schemes when the SNR is $\gamma_s = 20dB$. By comparing Fig. 5

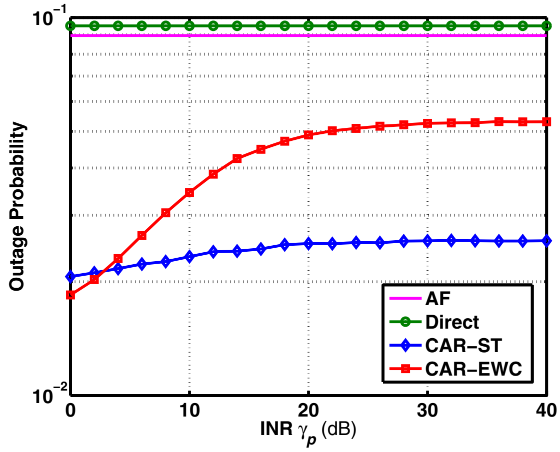

Fig. 4: Outage probabilities when the SNR is $\gamma_s = 10dB$.

with Fig. 4, it can be seen that with the increase of SNR, the effects of INR on the outage performance of each CAR scheme decrease. However, the MS is generally energy constrained and high power transmission can not be supported for a long time. It can be further observed from Fig. 6 that the CAR-EWC scheme performs even worse than the AF scheme without cognitive relay transmission when $\gamma_p \geq 16dB$. This is mainly because when γ_s increases from $\gamma_s = 10dB$ to $\gamma_s = 20dB$, the rated transmission power of the MS increases. As a result, the power of the amplified and forwarded interference increases with the increase of γ_p. However, since the relay is power constrained, the outage probability of each cognitive relay scheme approaches a constant when γ_p is large enough.

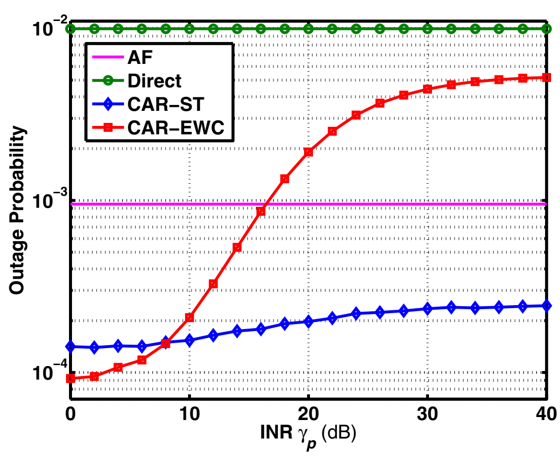

Fig. 5: Outage probabilities when the SNR is $\gamma_s = 20dB$.

VI. Conclusions

In this paper, we propose and compare two CAR schemes to improve the outage performance of MS in macrocellular networks. In the CAR-ST scheme, the MS transmits only over the LSB in the first stage, while in the second stage the relay amplifies and forwards its received signal over both the LSB and OSB. In the CAR-EWC scheme, the MS transmits over both the LSB and OSB in the first stage. In the second stage, the relay combines the signals received over the LSB and OSB with equal weight, and then the combined signal is amplified and forwarded over both the LSB and OSB. Our proposed CAR schemes exploit both the spectrum diversity and space diversity. Simulation results shows that compared with the direct transmission scheme and AF scheme that only exploit space diversity, our proposed CAR-EWC scheme and CAR-ST scheme can improve the outage performance of MS effectively when the INR is low and high, respectively. In future works, combining schemes that mitigate the negative effects of interference at the cognitive relay are expected.

Acknowledgment

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