Two-Way Spectrum Sharing Protocol in Overlay Cognitive Radio Network

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Abstract—**In this paper we propose a two-way spectrum sharing protocol for the overlay cognitive radio network consisting of two primary users (PUs) and two secondary users (SUs). One of the SUs acts as a relay to assist the communication between the PUs while at the same time allowing for two-way transmission with the other SU. The communication process is done in two phases. In the first phase, the PUs and the other SU are allowed to transmit simultaneously. The relay can use successive decoding to decode the message of the SU and then the PUs messages. In the second phase, the relay can use superposition coding to generate a new message composed of the XORed messages of the PUs and a new message for the SU. The performance of the protocol has been analyzed by deriving the outage probabilities of the PUs and SUs. Analytical and simulation results show that the proposed protocol offers efficient spectrum utilization and improved system capacity over the three-phase and two-phase spectrum sharing protocols with one-way SUs transmission in the literature.**

Keywords—Overlay cognitive radio; two-way relaying; cooperative communication; successive decoding; superposition coding.

I. Introduction

As the rapid growth of wireless communications to meet the fast growing demand for supporting an increasing number of advanced wireless applications and services, the availability of the radio spectrum becomes extremely scarce. Cognitive radio (CR) was proposed as a promising technology for enhancing the utilization of the radio spectrum, since it could efficiently resolve the spectrum scarcity versus under-utilization dilemma caused by the conventional fixed spectrum allocation [1].

The basic idea of CR is to allow secondary users (SUs) to opportunistically use the spectrum assigned to the primary users (PUs) whenever they are inactive or to share it with them even if they are active without degrading the performance of the PUs, such that the limited spectrum can be utilized more efficiently. Research on CR has been divided into three main spectrum-sharing paradigms: interweave, underlay, and overlay. The interweave paradigm, is based on opportunistic spectrum access (OSA) of the SUs to the frequency bands that are not in constant use by the PUs at the right time and the right location. The underlay and overlay paradigms, allow the SUs to transmit simultaneously with the PUs at the same band, where in the underlay model the SUs control their transmit power in such a way to limit its interference at the PUs receivers to an acceptable threshold. In the overlay model, the SUs are assumed equipped with advanced signal processing and encoding techniques to maintain or enhance the communication of the PUs while also gaining some bandwidth for their own communication [2].

The overlay model has been discussed in many research papers considering only one-way SUs transmission i.e. the transmission of the relay to the other SU [3]-[7]. In [4] the authors introduced two-way relaying overlay model in which the communication is performed in three phases. In the first and second phases, the PUs send their messages respectively to the relay, and the relay attempts to decode both signals. In the third phase, the relay broadcasts the physical-layer network coded (PNC) message of the PUs superimposed by the secondary signal. The outage probability, a spectrum sharing region and power allocation has been derived for such system. In [5] and [6], the authors proposed a two-phase two-way spectrum sharing overlay techniques. In [5] the authors suggested using adaptive relaying technique where in the first phase the relay attempts to decode both the simultaneously received primary signals and if successful, it will use DF relaying. However, if the decoding is not successful it will use amplify and forward AF scheme. In [6] the authors considered using analog network coding ANC in the first phase. The outage probability of the primary and secondary networks have been derived, and spectrum sharing regions within which the spectrum sharing protocol can achieve higher (or at least equal) outage performance for the primary users than direct transmission, have been identified.

In this paper we propose a two-way spectrum sharing protocol for the overlay CR paradigm where one of the SUs acts as a relay to assist the transmission between the PUs and at the same time allowing access for the SUs to the radio spectrum. The main contribution of this protocol is that besides maintaining the two-way transmission of the PUs it allows for two-way transmission between the SUs which offers efficient spectrum utilization and improved system capacity over the aforementioned protocols. Closed form expressions for the outage probabilities for both the PUs and SUs has been derived.

This paper is organized as follows. Section II presents the system model and proposed protocol description. The outage behavior of the primary and secondary users are presented in section III. The analytical and simulation results are discussed in section IV. Finally section V concludes the paper.

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II. System Model and Prtocol Description

In this paper we consider an overlay cognitive radio network as shown in Fig. 1, consisting of two PUs A and B, and two SUs C and D. C acts as a relay that cooperatively assists the transmissions between the PUs. Throughout this paper all nodes are constrained to operate in a half-duplex mode and having single antenna. We assume independent Rayleigh fading for all transmitter–receiver pairs. The channel coefficient between nodes i and j are denoted h_{ij} for $i,j \in \{A,B,C,D\}$ which is modeled as independent, circularly symmetric complex Gaussian random variables with zero mean and variances d_{ij}^{-v}, i.e., $h_{ij} \sim CN(0, d_{ij}^{-v})$[4], d_{ij} is the normalized distance between nodes i and j with respect to the distance between the primary users A and B, i.e., $d_{AB} = 1$, and v denotes the pathloss exponent which ranges from 2 to 5 depending on the type of the environment. The channel amplitudes $|h_{ij}|$are positive real random variables and follow a Rayleigh distribution with parameter d_{ij}^{-v}. We define the random variables $\gamma_{ij} = |h_{ij}|^2$, which are exponentially distributed with parameter d_{ij}^{v}. Also we assume channel reciprocity, i.e., $h_{ij} = h_{ji}$. Furthermore, the noise n_i at node $i \in \{A,B,C,D\}$ in any phase of transmission is modeled as independent circularly symmetric complex Gaussian random variables with zero mean and variance σ^2.

The overlay cognitive channel can be decomposed into two basic channels, Multiple Access Channel (MAC) and Broadcast Channel (BC). Therefore the communication process can be done in two phases as follows.

A. The MAC phase

The two PUs A and B and the SU D transmit their signals to the relay C, hence the received signal at C can be given as:

$$y_c = \sqrt{P_p} h_{AC} x_{Ak} + \sqrt{P_p} h_{BC} x_{Bq} + \sqrt{P_D} h_{DC} x_D + n_C \qquad (1)$$

where x_{Ak} and x_{Bq} are the k[th] and q[th] unit power symbols from the M-ary constellation used at A and B respectively. Also x_D is a unit power symbol from the M-ary constellation used at D. P_p *and* P_D are the transmit powers of the PUs (A,B) and the SU D, respectively.

The relay C will use successive decoding to first decode the desired signal x_D from y_c while considering x_{Ak} and x_{Bq} as interference, so the Signal to Interference Noise Ratio (SINR) is:

$$\Gamma_{DC} = \frac{\eta_D \gamma_{DC}}{\eta_p(\gamma_{AC} + \gamma_{BC}) + 1} \qquad (2)$$

where $\eta_p = \frac{P_p}{\sigma^2}$, $\eta_D = \frac{P_D}{\sigma^2}$, $\gamma_{ij} = |h_{ij}|^2$ *for* $i,j \in (A,B,C,D)$

Thus the maximum average mutual information between D and C is:

$$I_{DC} = \frac{1}{2} log_2(1 + \Gamma_{DC}) \qquad (3)$$

where the factor of ½ accounts for the fact that each transmission from D to C occurs only in the first phase compared to the overall transmission which consists of two phases.

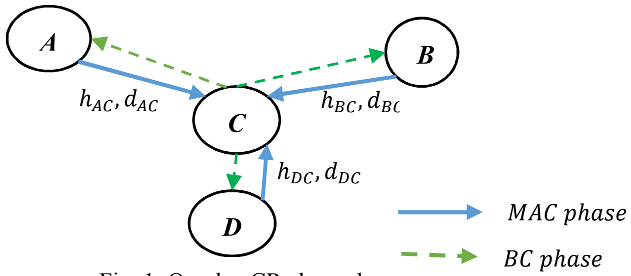


Fig. 1. Overlay CR channel

If C successfully decodes x_D, it will subtract it from y_C to get:

$$y_c' = \sqrt{P_p} h_{AC} x_{Ak} + \sqrt{P_p} h_{BC} x_{Bq} + n_C \qquad (4)$$

And then from y_c' the relay C tries to decode for both x_{Ak} and x_{Bk} using optimal detection based on ML principle as follows:

$$[\hat{k}, \hat{q}] = \underset{k,q}{\operatorname{argmin}} \left| y_c' - \sqrt{P_p}(h_{AC} x_{Ak} + h_{BC} x_{Bq}) \right|^2 \qquad (5)$$

Then if C successfully decodes the data of A and B it computes $p = \hat{k} \oplus \hat{q}$ to obtain the p[th] symbol x_p from the M-ary constellation used at A and B to be transmitted in the BC phase.

B. The BC phase

The relay C wants to transmit the symbol x_p obtained from the first phase to both PUs A and B and also to transmit its own messaeg x_{CD} to the SU D. Therefore the relay C will use superposition coding to assign part of its transmit power P_s to relay the symbol x_p and the remaining part for transmitting its own symbol x_{CD}. i.e. C generates the composite signal $x_c = \sqrt{\alpha P_s} x_p + \sqrt{(1-\alpha) P_s} x_{CD}$, where α $(0 \le \alpha \le 1)$ is the power split factor, and x_{CD} is a zero mean unit power signal intended for the SU D. Therefore the corresponding received signal at receiver $j = \{A,B,D\}$ can be expressed as:

$$y_j = \sqrt{\alpha P_s} h_{Cj} x_p + \sqrt{(1-\alpha) P_s} h_{Cj} x_{CD} + n_j \qquad (6)$$

The PUs A and B decodes directly for the symbol x_p from y_A and y_B respectively to obtain $\hat{p}$ from which they make XOR operation with their own data to obtain the other user's data. While D first decodes for the symbol x_p from y_D and then cancels it from y_D and then decode for its desired symbol x_{CD}. Hence the maximum average mutual information between C and user $j = (A,B,D)$ to decode for the symbol x_p can be given as:

$$I_{Cj} = \frac{1}{2} log_2 \left(1 + \frac{\alpha \eta_s \gamma_{Cj}}{(1-\alpha)\eta_s \gamma_{Cj} + 1}\right) \qquad (7)$$

where $\eta_s = \frac{P_s}{\sigma^2}$. For the SU D after successfully decoding for the symbol x_p it will subtract it from the received signal to get $y_D' = \sqrt{(1-\alpha) P_s} h_{CD} x_{CD} + n_j$, from which it will decode for x_{CD}. Hence the maximum average mutual information between C and D to decode for x_{CD} conditioned on the correct decoding of the symbol x_p can be given by:

$$I'_{CD} = \frac{1}{2} log_2 \left(1 + \frac{(1-\alpha) P_s \gamma_{CD}}{\sigma^2}\right) \qquad (8)$$

III. OUTAGE BEHAVIOR

In this part we analyze the performance of the above described protocol in terms of outage events and outage probabilities. We assume that the target rate for the PUs is R_{pt} while for the SUs is R_{st}. Therefore an outage event occurs when the maximum average mutual information for a link is less than the target rate of that link ($I < R_{target}$).

A. Outage probability of the secondary users

The Outage probability of C to decode the message of D in the MAC phase can be expressed as follows using (2) and (3):

$$P_{OUT-C}^{D} = Pr(I_{DC} < R_{st}) = Pr(\Gamma_{DC} < R_s)$$

$$= 1 - \frac{\eta_D^2\, d_{AC}^v\, d_{BC}^v}{(\eta_p\, d_{DC}^v\, R_s + \eta_D\, d_{AC}^v)((d_{BC}^v + \eta_p)\, d_{DC}^v\, R_s + \eta_D\, d_{BC}^v)} \quad (9)$$

where $R_s = 2^{2R_{st}} - 1$, and we utilized the CDF of the random variable $\Gamma_{DC} = \frac{U}{V+W}$, where $U = \eta_D \gamma_{DC}, V = \eta_p \gamma_{AC}$ and $W = \eta_p \gamma_{BC} + 1$ are exponential random variables with parameters $\lambda_u = \frac{d_{DC}^v}{\eta_D}$, $\lambda_v = \frac{d_{AC}^v}{\eta_p}$, and $\lambda_w = \frac{d_{BC}^v}{d_{BC}^v + \eta_p}$ respectively, which can easily be derived as:

$$F_{\Gamma_{DC}}(z) = 1 - \frac{\lambda_v \lambda_w}{(\lambda_u z + \lambda_v)(\lambda_u z + \lambda_w)} \quad (10)$$

To calculate the Outage probability of D to decode the message of C in the BC phase, we recall what we mentioned in section II that D uses successive decoding in the BC phase to decode the symbol x_p first and then x_{cd}, hence the outage probability of D can be written as:

$$P_{OUT-D}^{C} = 1 - Pr(I_{DC} > R_{st}) Pr(I_{AC} > R_{pt}) Pr(I_{BC} > R_{pt})$$

$$\times Pr(I_{CD} > R_{pt}) Pr(I'_{CD} > R_{st}) \quad (11)$$

where,

$$Pr(I_{AC} > R_{pt}) = Pr\left(\gamma_{AC} > \frac{R_p}{\eta_p}\right) = exp\left(-\frac{R_p\, d_{AC}^v}{\eta_p}\right) \quad (12)$$

$$Pr(I_{BC} > R_{pt}) = Pr\left(\gamma_{BC} > \frac{R_p}{\eta_p}\right) = exp\left(-\frac{R_p\, d_{BC}^v}{\eta_p}\right) \quad (13)$$

$$Pr\{I_{CD} > R_{pt}\} = Pr\left(\frac{\alpha \eta_s \gamma_{CD}}{(1-\alpha)\eta_s \gamma_{CD} + 1} > R_p\right)$$

$$= \begin{cases} exp\left(-\frac{d_{CD}^v R_p}{\eta_s(\alpha(1+R_p) - R_p)}\right), & if \quad \frac{R_p}{R_p+1} < \alpha < 1 \\ 0 & , if \quad 0 < \alpha \le \frac{R_p}{R_p+1} \end{cases} \quad (14)$$

where after some manipulations we can obtain the above expression. And using (8) we have

$$Pr(I'_{CD} > R_{st}) = exp\left(-\frac{d_{CD}^v R_s}{(1-\alpha)\eta_s}\right) \quad (15)$$

where $R_p = 2^{2R_{pt}} - 1$, $R_s = 2^{2R_{st}} - 1$. Since γ_{ij} is an exponential random variable with parameter d_{ij}^v we have $Pr(\gamma_{ij} > R) = exp(-d_{ij}^v R)$.

From (9), (12)-(15) into (11) we obtain:

$$P_{OUT-D}^{C} = \begin{cases} 1 - exp\left(-\frac{d_{CD}^v R_p}{\eta_s(\alpha(1+R_p) - R_p)} - \frac{d_{CD}^v R_s}{(1-\alpha)\eta_s} - \frac{R_p(d_{AC}^v + d_{BC}^v)}{\eta_p}\right) \\ \quad \times \frac{\eta_D^2\, d_{AC}^v\, d_{BC}^v}{(\eta_p\, d_{DC}^v\, R_s + \eta_D\, d_{AC}^v)((d_{BC}^v + \eta_p)\, d_{DC}^v\, R_s + \eta_D\, d_{BC}^v)} & , if \quad \frac{R_p}{R_p+1} < \alpha < 1 \\ 1 & , if \quad 0 < \alpha \le \frac{R_p}{R_p+1} \end{cases} \quad (16)$$

B. Outage probability of the Primary Users

The Outage probability of A to decode the message of B through the cooperation with C can be computed as follows:

$$P_{OUT-A}^{B} = 1 - Pr(I_{DC} > R_{st}) Pr(I_{AC} > R_{pt})$$

$$\times Pr(I_{BC} > R_{pt}) Pr(I_{CA} > R_{pt}) \quad (17)$$

where $Pr\{I_{CA} > R_{pt}\} = Pr\left(\frac{\alpha \eta_s \gamma_{CA}}{(1-\alpha)\eta_s \gamma_{CA} + 1} > R_p\right)$

$$= \begin{cases} exp\left(-\frac{d_{CA}^v R_p}{\eta_s(\alpha(1+R_p) - R_p)}\right) & , if \quad \frac{R_p}{R_p+1} < \alpha < 1 \\ 0 & , if \quad 0 < \alpha \le \frac{R_p}{R_p+1} \end{cases} \quad (18)$$

Substituting equations (9), (12), (13) and (18) into (17), we obtain:

$$P_{OUT-A}^{B} = 1 - \left[\frac{\eta_D^2\, d_{AC}^v\, d_{BC}^v}{(\eta_p\, d_{DC}^v\, R_s + \eta_D\, d_{AC}^v)((d_{BC}^v + \eta_p)\, d_{DC}^v\, R_s + \eta_D\, d_{BC}^v)}\right.$$

$$\left.\times\, exp\left(-\frac{R_p(d_{AC}^v + d_{BC}^v)}{\eta_p}\right) exp\left(-\frac{d_{CA}^v R_p}{\eta_s(\alpha(1+R_p) - R_p)}\right)\right]$$

$for \quad \frac{R_p}{R_p+1} < \alpha < 1$, and 1 elsewhere. (19)

In a similar way we can obtain the outage probability of B to decode the message of A as:

$$P_{OUT-B}^{A} = 1 - \left[\frac{\eta_D^2\, d_{AC}^v\, d_{BC}^v}{(\eta_p\, d_{DC}^v\, R_s + \eta_D\, d_{AC}^v)((d_{BC}^v + \eta_p)\, d_{DC}^v\, R_s + \eta_D\, d_{BC}^v)}\right.$$

$$\left.\times\, exp\left(-\frac{R_p(d_{AC}^v + d_{BC}^v)}{\eta_p}\right) exp\left(-\frac{d_{CB}^v R_p}{\eta_s(\alpha(1+R_p) - R_p)}\right)\right]$$

$for \quad \frac{R_p}{R_p+1} < \alpha < 1$, and 1 elsewhere. (20)

IV. SIMULATION RESULTS AND DISCUSSION

To evaluate the performance of the proposed protocol we have conducted simulations for the outage probability of the PUs and SUs. For comparison purposes the outage probability of the primary user A (B) to decode the message of B (A) without spectrum sharing can be computed as follows:

$$P_{outA-\text{direct}} = P_{outB-\text{direct}} = Pr(I_{AB} < R_{pt})$$

$$= Pr\left(\frac{1}{2}log_2(1+\eta_p\gamma_{AB}) < R_{pt}\right) = 1 - exp\left(-\frac{R_p}{\eta_p}\right) \quad (22)$$

We consider the outage performance of the PUs and SUs for the network shown in Fig.1, with various parameters for distances, SNRs and target rates. For all simulations and analytical expressions the path loss exponent is taken as $v = 4$.

Fig. 2(a, b, and c) show the outage performance of the system at $\eta_p = 15\ dB$, $\eta_s = \eta_D = 30dB$, $d_{AC} = d_{BC} = 0.5, d_{DC} = 0.1$, and target rates $R_{pt} = R_{st} = 0.5, 1\ and\ 2$ b/s/Hz respectively. In all cases we can see that the proposed protocol provides better performance for the PUs compared to the case of direct transmission and we observe that the analytical results are in agreement with the simulation results. The optimum value of the power split factor α (as $\frac{R_p}{R_p+1} < \alpha < 1$) can be obtained from the outage probability of the SU D in the BC phase. Conditioned on the successful decoding of the relay C in the MAC phase the outage probability of the SU D in the BC phase can be expressed as, $P^{C}_{OUT-D}|\ Condisioned\ on\ C = 1 - Pr(I_{CD} > R_{pt})Pr(I'_{CD} > R_{st})$. For Fig. 2 (a, b, and c), we can observe that $\alpha_{opt} = 0.7, 0.84\ and\ 0.95$, resectively. Also we can see that as α exceeds the threshold $\frac{R_p}{R_p+1}$, the outage probability of D first decreases with increasing α until $(\alpha = \alpha_{opt})$ and then increases to 1. This is due to the fact that D uses successive decoding in the second phase. As α increases above the threshold $\frac{R_p}{R_p+1}$ and below α_{opt}, the allocated power for the XORed primary symbol increases and the allocated power for the secondary message decreases but still good enough for the detection of the secondary message x_{CD} at D. When α exceeds α_{opt}, the allocated power for the secondary signal decreases until D becomes unable to decode x_{CD}, so the outage probability increases to 1. Also we can observe that the overall outage probability of the SU D given by (11) appears to remain constant as $\frac{R_p}{R_p+1} < \alpha < 1$, since the value of the probabilities $Pr(I_{CD} > R_{pt}) \to 1$ and $Pr(I'_{CD} > R_{st}) \to 1$ as $d^{v}_{DC} \to 0$ in (11), hence the dependence on α becomes unnoticeable.

Fig. 3(a) shows that as the distance between C and D increases from $d_{DC} = 0.1$ to 0.5 with same other parameters as for Fig. 2-a, the performance gets worse since C is unable to decode SU and PUs messages and hence the outage probability increases for all users. In this case D is required to increase its transmit power as shown in Fig. 3(b) to provide a strong interference channel letting C able to decode both messages.

V. CONCLUSION

In this paper we proposed a two-way spectrum sharing protocol for the overlay cognitive two-way two-phase channel which allows for two-way SUs communication while assisting the communication between the PUs. Closed form expressions for the outage probabilities for both the PUs and SUs has been derived. Analytical and simulation results show that the proposed protocol offers efficient spectrum utilization (and hence higher system capacity) over the three-phase and two-phase spectrum sharing protocols in literature with one-way SUs transmission.

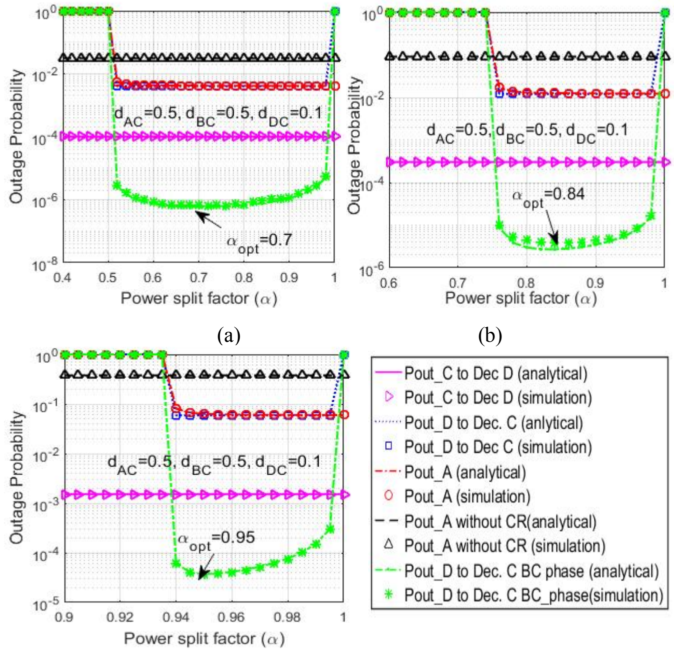
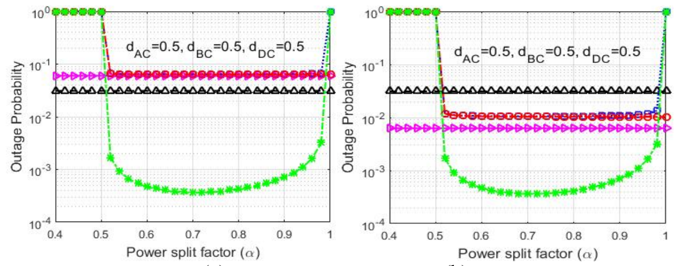


Fig. 2, Outage probability vs. power split factor for $\eta_p = 15\ dB$, $\eta_s = \eta_D = 30dB$, $d_{AC} = d_{BC} = 0.5, d_{DC} = 0.1$. (a) $R_{pt} = R_{st} = 0.5$ b/s/Hz. (b) $R_{pt} = R_{st} = 1$ b/s/Hz. (c) $R_{pt} = R_{st} = 2$ b/s/Hz (d) Legend for all figures.



(a) (b)

Fig. 3, Outage probability vs. power split factor for $\eta_p = 15\ dB$, $\eta_s = 30dB$, $d_{AC} = d_{BC} = 0.5, d_{DC} = 0.5. R_{pt} = R_{st} = 0.5$ b/s/Hz. (a) $\eta_D = 30dB$ (b) $\eta_D = 40dB$.

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