POSITION-BASED SPECTRUM SHARING ANALYSIS IN MULTI-USER MIMO COGNITIVE RADIO SYSTEMS

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Received: February 02, 2018; Revised: April 05, 2018; Accepted: April 05, 2018

Abstract

This paper introduces the performance analysis of multi-user spectrum sharing based the effect of node positions in MIMO cognitive radio (CR) network. The objective is to make a CR technology become reliable and closer to the reality. The authors have developed the performance analysis that supports both of non-overlapping and overlapping spectrum sharing, and also evaluated data in term of node positions inside the coverage area. Which the advantages that enhance the existing works are 1) this paper develops the performance analysis to support multi-user CR systems, 2) it describes the significant effect of each node position and the distance between them, and 3) it combines the decision results on both downlink and uplink operations. The simulation results show the performance of secondary users in terms of the bit error rate inside the coverage area and the comparison result between the non-overlapping and overlapping cases. The outcome of this paper is very useful to enhance CR system. Also, it can be easily implemented in practice at the state of spectrum sharing. The users can be realized by themselves whether their positions are in the available area or not.

Keywords: Cognitive radio, MIMO, spectrum sharing, multi-user communication, bit error rate

Introduction

After the spectrum sensing process, the CR system can identify whether the considered channel is available or occupied by the primary user (PU). If the channel is available, secondary user (SU) will operate the non-overlapping spectrum sharing, hence the

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interferences will only appear within the SUs due to themselves. On the other hand, if the channel is occupied, it will operate the overlapping spectrum sharing, which the interference from each SU will affect PU and each SU will cause interference to PU as well. Hence, there are many works in literature to propose the interference reduction methods (Zhang *et al.*, 2009; Puranachaikeeree, 2010). The authors in (Khan *et al.*, 2014; Tourki *et al.*, 2014) have introduced the performance analysis of the transmitting power constraint in spectrum sharing with a transmitting antenna selection technique at the secondary transmitter (ST) and the maximum ratio combining technique at secondary receiver (SR). It can be seen that the interference level is up to the transmitting power of each user in the system, many works have focused on the power control of SU. In (Khalfi *et al.*, 2015; Kim *et al.*, 2015; Yang *et al.*, 2015; Vassaki *et al.*, 2016), the works have developed power allocation schemes to support multi-user CR systems. However, the existing works have just discussed in the terms of defined power that is not increased or decreased by distances or positions, especially in (Khan *et al.*, 2014; Tourki *et al.*, 2014). They assume the powers of both interferences and users to be constant throughout their equations and experiments. This may be a big problem in practice because only a few limited areas will have such a nature. In fact, PU and SU are roaming in any areas around the base station (BS) and fusion center (FC). So, most of the areas are outage based on the specific conditions of assumed powers. This has happened even the adaptive power allocation can be efficiently employed. However, there are some positions that are not outage for SUs. If SUs can realize the available area to operate the spectrum sharing, it will cause many benefits to the system. So far, there have not been any works to present the performance analysis in multi-user CR systems based on positions.

In this paper, the authors have taken the effect of positions of BS, PU, FC, and SUs into the performance analysis of spectrum sharing for multi- user MIMO CR systems. The simulation results show the signal quality in terms of bit error rate (BER) which can get along with the position information on both downlink and uplink operations. Then, the intersection result from the performance analysis on downlink and uplink can be the good guideline to avoid the terrible damage in multi-user communication.

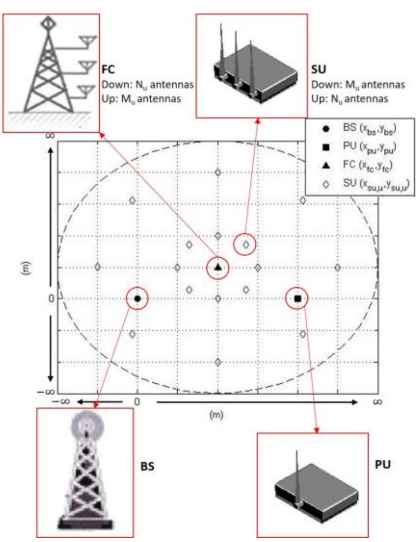

Figure 1. Multi-user spectrum sharing CR system model

Materials and Method

System Model

The primary link is composed of only one antenna for both primary transmitter (PT) and primary receiver (PR). Whereas, each secondary

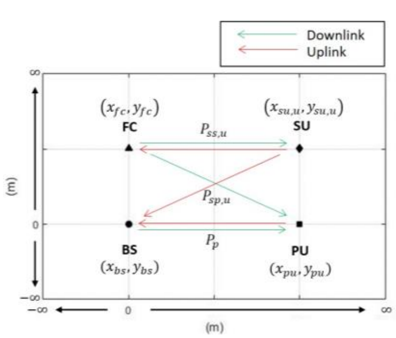

Figure 2. Position allocations of each member in multi-user MIMO CR systems

link is composed of ST and SR, which is equipped with N_u and M_u antennas, respectively, that belong to each SU from overall U number of SUs in a coverage area of FC, when u =1,2,…, U, as seen in Figure 1. It can be seen that the number of antennas of each SU is not necessary to be the same as each other, but it not less than 2 antennas to support the MIMO systems.

For the downlink, BS is defined as PT, FC is defined as ST, PU is defined as PR, and SUs are defined as SRs. The channel between the antennas of FC and the antennas of u^{th} SU has a variance σ_s^2. The channel between the antennas of FC and the antenna of PU has a variance σ_{sp}^2. The channel between an antenna of BS and the antennas of u^{th} SU has a variance σ_{sp}^2.

For the uplink, BS is defined as PR, FC is defined as SR, PU is defined as PT, and SUs are defined as STs. The channel between the antennas of u^{th} SU and the antennas of FC has a variance σ_s^2. The channel between the antennas of u^{th} SU and an antenna of BS has a variance σ_s^2. The channel between an antenna of PU and the antennas of FC has a variance σ_{sp}^2. The channel between the antennas of other SUs in the same coverage area and the antennas of FC has a variance σ_{is}^2.

For more clarity as shown in Figure 2, the received power of primary link for both downlink and uplink, which use the free-space propagation model, are given as

$$P_p = P_{max}\left(\frac{\lambda}{4\pi R_p}\right)^2 G_t G_r, \qquad (1)$$

where P_{max} is a maximum primary output power, λ is wavelength, R_p is the distance between PT to PR, G_t and G_r are transmitter gain and receiver gain, respectively.

For both downlink and uplink, the distance from PT to SR is $D_{ps,u}$, and the distance from ST to SR is $D_{ss,u}$. Hence, their received powers from both distances are given as

$$P_{ps,u} = P_{max}\left(\frac{\lambda}{4\pi D_{ps,u}}\right)^2 G_t G_r, \qquad (2)$$

$$P_{ss,u} = P_{smax}\left(\frac{\lambda}{4\pi D_{ss,u}}\right)^2 G_t G_r, \qquad (3)$$

which P_{smax} is a maximum secondary output power. But only for uplink, it has the interference power vector due to other SUs in the same coverage area, which can be defined as

$$\mathbf{P}'_{ssI\_u} = \mathbf{P}'_{ss\_u} - \begin{bmatrix} 0 & \cdots & P_{ss,u\_u} & 0 & \cdots & 0 \end{bmatrix}, \qquad (4)$$

where $P_{ss,u\_u} \in \boldsymbol{P}_{ss\_u}$. In order to avoid any confusion, we have added subscript $\_u$ into the power variables and power matrices representing for the uplink.

Performance Analysis

To evaluate BER, the m-QAM modulation is employed, where m is constellation size. Then the received power from ST to PR is given by

$$P_{sp} = \left(\frac{-1.5 P_p G_c}{(m-1)\ln\left(5BER_p\right)} - N_o\right)\frac{1}{\sigma_{sp}^2}, \qquad (5)$$

where G_c is the coding gain (Goldsmith, 2005, Eq. 9.38), and N_o is the power spectral density of the noise assumed to be constant and the same for all states. After that, considering the power from (5), we can find the BER region of primary network due to interference from ST in the same location by using

$$D_{sp} = \frac{\lambda}{4\pi}\left(\frac{P_{smax} G_t G_r}{P_{sp}}\right)^{\frac{1}{2}}. \qquad (6)$$

By using PR as a reference point, the distance from ST to PR D_{sp} from (6) will show the possible position of ST that can be available to communicate with FC around PR.

Hence, we can predict the positions of ST that affect to PR satisfaction.

The Cumulative Distributed Function (CDF) of σ_s^2 (Tourki *et al.*, 2014, Eq. 5) is given by

$$F_{\sigma_s^2}(x)=\frac{1}{\Gamma(M_u+1)}\left[\left(\frac{x}{\sigma_s^2}\right)^{M_uN_u}\Gamma\left(1-M_u(N_u-1),\frac{x}{\sigma_s^2}\right)+\gamma\left(M_u+1,\frac{x}{\sigma_s^2}\right)\right]. \quad (7)$$

where $\Gamma(\ )$ is the gamma function, $\Gamma(\ ,\ )$ and $\gamma(\ ,\ )$ are the upper incomplete gamma function and the lower incomplete gamma function, respectively.

Only in the non-overlapping spectrum sharing case, when interference from PT-SR is ignored ($P_{ps,u}$ = 0), BER of this case on downlink can be expressed as

$$BER_{s,u}(a,b)=\frac{a}{2}\sqrt{\frac{b}{2\pi}}\int_0^\infty\frac{e^{-\frac{b}{2}x}}{\sqrt{x}}F_{\sigma_s^2}\left(\frac{x}{\frac{P_{ss,u}}{N_0}}\right)dx. \quad (8)$$

where a and b are the modulation-specific constants, such as (a,b) = (1,2) for BPSK, (a,b) = (1,1) for BFSK, and (a,b) = (2(m-1)/m, 6log$_2$(m)/(m^2-1)) for m-PAM. Using (Gradshteyn, 2007, Eq. 6.455.1 and Eq. 6.455.2), so the BER in (8) will be the closed form as

$$BER_{s,u}(a,b)=\frac{\Gamma\left(M_u+\frac{3}{2}\right)}{\Gamma(M_u+1)}\frac{\frac{a}{2}\sqrt{\frac{b}{2\pi}}\left(\frac{1}{\gamma_{ss,u}}\right)^{1+M_u}}{\left(\frac{1}{\gamma_{ss,u}}+\frac{b}{2}\right)^{M_u+\frac{3}{2}}}\left[\left(\frac{1}{M_uN_u+\frac{1}{2}}\right)\right. \quad (9)$$
$$\times{}_2F_1\left(1,M_u+\frac{3}{2};M_uN_u+\frac{3}{2};\frac{b\gamma_{ss,u}}{2+b\gamma_{ss,u}}\right)$$
$$\left.+\left(\frac{1}{1+M_u}\right){}_2F_1\left(1,M_u+\frac{3}{2};M_u+2;\frac{2}{2+b\gamma_{ss,u}}\right)\right],$$

where ${}_2F_1$(.,.;.;.) is the hypergeometric function. Then, SNR from ST-SR link for both downlink and uplink are defined as

$$\gamma_{ss,u}=\sigma_s^2\frac{P_{ss,u}}{N_0}. \quad (10)$$

For overlapping spectrum sharing case, when interference from PT-SR is considered ($P_{ps,u}\neq 0$), SNR from PT-SR on downlink is expressed by

$$\gamma_{is,u\_d}=\sigma_{ps}^2\frac{P_{ps,u\_d}}{N_0}, \quad (11)$$

which the subscription *_d* represents the downlink. For the uplink of both spectrum sharing cases, SNR is defined as

$$\gamma_{is,u\_u}=\sigma_{ps}^2\frac{P_{ps,u\_u}}{N_0}+\sigma_{is}^2\sum_{u=1}^{U}\frac{P_{ssI,u\_u}}{N_0}. \quad (12)$$

Note that $P_{ps,u}$ = 0 in (12) only for uplink of non-overlapping case.

The BER of overlapping cases for downlink and uplink can be expressed in

$$BER_{Int,u}(a,b)=\frac{a}{2}\sqrt{\frac{b}{2\pi}}\int_0^\infty\frac{e^{-\frac{b}{2}x}}{\sqrt{x}}\int_0^\infty\frac{e^{-\frac{y}{\gamma_{is,u}}}}{\gamma_{is,u}}F_{\sigma_s^2}\left(\frac{x(y+1)}{\frac{P_{ss,u}}{N_0}}\right)dydx. \quad (13)$$

By using (Gradshteyn, 2007, Eq. 8.352.5, Eq. 8.352.4, Eq. 3.352.1, Eq. 6.228.2, Eq. 3.383.5, and Eq. 3.352.2) to get

$$BER_{Int,u}(a,b)=\frac{a}{2}\sqrt{\frac{b}{2\pi}}\frac{1}{\Gamma(M_u+1)}\left[I_{1,u}+I_{2,u}+I_{3,u}+I_{4,u}\right], \quad (14)$$

which is the same as non-overlapping case for uplink, where

$$I_{1,u}=\frac{(-1)^{M_u(N_u-1)+1}}{(M_u(N_u-1)-1)!}e^{\frac{1}{\gamma_{is,u}}}\left(\frac{\gamma_{is,u}}{\gamma_{ss,u}}\right)^{M_uN_u}\frac{\Gamma\left(M_uN_u+1,\frac{1}{\gamma_{is,u}}\right)}{\left(M_uN_u+\frac{1}{2}\right)}$$
$$\times\frac{\Gamma\left(M_uN_u+\frac{1}{2}\right)}{\left(\frac{1}{\gamma_{ss,u}}+\frac{b}{2}\right)^{M_uN_u+\frac{1}{2}}}{}_2F_1\left(1,M_uN_u+\frac{1}{2};M_uN_u+\frac{3}{2};\frac{b\gamma_{ss,u}}{2+b\gamma_{ss,u}}\right), \quad (15)$$

where ${}_2F_1$(.,.;.;.) is the hypergeometric function. Next,

$$I_{2,u} = (-1)^{M_u(N_u-1)} (M_u N_u)!\Gamma\left(M_u N_u + \frac{1}{2}\right) e^{\frac{b\gamma_{ss,u}+2}{4\gamma_{is,u}}} \sum_{k=1}^{M_u N_u} \frac{(k-1)!}{k!}$$
$$\times \sum_{m=0}^{k-1} \frac{\left(\frac{1}{\gamma_{is,u}}\right)^m}{m!} \left(\frac{1}{\gamma_{ss,u}} + \frac{b}{2}\right)^{-\frac{1}{2}\left(M_u N_u + m - k + \frac{3}{2}\right)} \left(\frac{\gamma_{ss,u}}{\gamma_{is,u}}\right)^{\frac{1}{4}(2k+2m-2M_u N_u - 1)}$$
$$\times W_{\frac{1}{2}\left(m-k-M_u N_u - \frac{1}{2}\right), -\frac{1}{2}\left(M_u N_u + m - k + \frac{1}{2}\right)} \left(\frac{b\gamma_{ss,u}+2}{2\gamma_{is,u}}\right), \tag{16}$$

$$I_{3,u} = \left(\frac{1}{\gamma_{is,u}}\right) e^{\frac{b\gamma_{ss,u}+2}{4\gamma_{is,u}}} \sum_{k=0}^{M_u(N_u-1)-2} (-1)^{M_u(N_u-1)+k} k!(M_u N_u - k - 1)!$$
$$\times \Gamma\left(M_u N_u - k - \frac{1}{2}\right) \sum_{m=0}^{M_u N_u - k - 1} \frac{\gamma_{ss,u}^{1-m}}{m!} \left(\frac{1}{\gamma_{ss,u}} + \frac{b}{2}\right)^{-\frac{1}{2}\left(m+\frac{1}{2}\right)}$$
$$\times \left(\frac{\gamma_{ss,u}}{\gamma_{is,u}}\right)^{\frac{1}{2}\left(m-\frac{3}{2}\right)} W_{\frac{1}{2}\left(2k-2M_u N_u + m + \frac{3}{2}\right), \frac{1}{2}\left(-m+\frac{1}{2}\right)} \left(\frac{b\gamma_{ss,u}+2}{2\gamma_{is,u}}\right), \tag{17}$$

and

$$I_{4,u} = M_u! \left[\sqrt{\frac{2\pi}{b}} - \left(\frac{1}{\gamma_{is,u}}\right) e^{\frac{b\gamma_{ss,u}+2}{4\gamma_{is,u}}} \sum_{k=0}^{M_u} \Gamma\left(k + \frac{1}{2}\right) \sum_{m=0}^{k} \frac{\gamma_{ss,u}^{-m+1}}{m!}\right.$$
$$\left. \times \left(\frac{1}{\gamma_{ss,u}} + \frac{b}{2}\right)^{-\frac{1}{2}\left(m+\frac{1}{2}\right)} \left(\frac{\gamma_{ss,u}}{\gamma_{is,u}}\right)^{\frac{1}{2}\left(m-\frac{3}{2}\right)} W_{\frac{1}{2}\left(m-2k-\frac{1}{2}\right), \frac{1}{2}\left(-m+\frac{1}{2}\right)} \left(\frac{b\gamma_{ss,u}+2}{2\gamma_{is,u}}\right)\right], \tag{18}$$

where $W_{\varepsilon,\mu}(\,)$ is the Whittaker W-function.

However, there are some limitations that this work support only spectrum sharing for multi-user one-cell CR systems, but it does not support in multi-user multi-cell CR systems. And this work based on the assumption that the primary link is composed of only one antenna for both BS and PU.

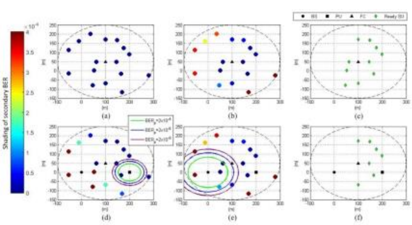

Figure 3. Spectrum sharing for multi-user CR systems for non-overlapping operation, (a) downlink, (b) uplink, and (c) their intersection and for overlapping operation, (d) downlink, (e) uplink, and (f) their intersection

Results and Discussion

The channel model in simulations is based on LTE standard (ETSI, 2011), which defines the system parameters including: 1920-1980 MHz for uplink operating band, 2110-2170 MHz for downlink operating band, 23 dBm for maximum transmitted power, -103.535 dBm for minimum received power, the maximum number of MIMO element is 4×4 and the tolerated BER = 2×10^{-4}.

In this work, the authors define FC is equipped with 4 antennas, $\sigma_s^2 = 1$ for the considered channels, $\sigma_{sp}^2 = \sigma_{ps}^2 = \sigma_{is}^2 = 0.01$ for the interference channels, $(a,b) = (1,2)$ that we assume only the secondary link communication uses BPSK modulation, $G_t = 0$ dB, $G_r = 6$ dB, and the GPS error around 0-3 m referred to the current GPS device accuracies. By using MATLAB program for simulations.

The BER of SUs in case of non-overlapping spectrum sharing is presented in Figure 3(a) and Figure 3(b) for downlink and uplink, respectively. This non-overlapping case will be operated only when the system does not sense any power of PU in spectrum sensing process. Therefore, this case does not consider a primary link in calculation due to no any interference to SUs on the downlink.

In turn, each SU makes the interference to each other on uplink. This caused some SUs to have BER more than 2×10^{-4}. Then, the intersection result of available SUs between downlink in Figure 3(a) and uplink in Figure 3(b) is shown in Figure 3(c). It is obvious that only some SUs can be available to make a communication under the case of non-overlapping spectrum sharing.

Next, the case of overlapping spectrum sharing is investigated by assuming $m = 16$ for m-QAM modulation used by the primary link communication, $G_c = 6$ dB and 0 dBm for transmitted power of BS. Figure 3(d) and Figure 3(e) show the BER results of SUs for downlink and uplink, respectively. Unlike the previous case, there is PU active in the system then it influenced the secondary link, and the primary link will be taken the effect of secondary link too. For downlink in Figure 3(d), there are the circles around PU that indicate BER = 2×10^{-4}, 2×10^{-6}, and 2×10^{-8}. If PU walks into FC too closely, the FC will have to access other frequency channels, non-overlapping mode, in order to avoid the undesirable interference to primary link. Also noticed in this figure, there are some SUs having BER more than 2×10^{-4} due to the interferences from BS which are not recommended to establish communication on this spectrum. Apart from these SUs, the others in different positions are available to operate MIMO CR communications. For uplink in Figure 3(e), if SUs stay inside the circle that BER = 2×10^{-4}, these SUs cannot operate the spectrum sharing due to the interferences from PU and the other nearby SUs. Finally, the intersection result of available SUs between Figure 3(d) and Figure 3(e) is shown in Figure 3(f). It is observed that some SUs can perform overlapping spectrum sharing under successful operation on both downlink and uplink. This is based on each SU position under the condition that BER of PU will not be less than BER = 2×10^{-4}.

The results in Figure 3(c) and Figure 3(f) can reveal that some available SUs in the non-overlapping case will be not available in the overlapping case because of two main causes including the impact of interference from PT which makes the BER of secondary links more than 2×10^{-4} and the bad positions of those SUs which stay inside the prediction line of BER_p = 2×10^{-4}. However, both figures have shown the good guideline for making a decision in multi-user communication.

Conclusions

The position-based performance analysis for both non-overlapping and overlapping spectrum sharing techniques is presented in this paper. The mathematical solution shows the relationship between BER and user positions. The simulation results can describe the interference impact of each user in CR systems related to a thorough performance analysis in terms of BER that supports both downlink and uplink operations. The results are very useful for multi-user MIMO CR implementation to make a decision whether its current position is suitable to establish a communication or not.

Acknowledgements

The authors acknowledge the School of Telecommunication Engineering, Suranaree University of Technology, Thailand, for their full support during the work.

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