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Self-evaluation guideline of overlapping spectrum sharing for multi-user MIMO cognitive radio systems

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Abstract

This paper introduces a performance analysis of a multi-user spectrum sharing based the effect of node positions in an MIMO cognitive radio (CR) network. The objective is to develop and enable reliable CR technology. This paper: 1) develops the performance analysis to support multi-user CR systems, 2) describes the significant effect of each node position and the distance between them, 3) combines decision results on both downlink and uplink operations, and, 4) presents a spectrum allocation method for all users in CR systems. The simulation results show the performance of secondary users in terms of the bit error rate inside their coverage areas together with the effect of GPS error. Finally, a complete self-evaluation guideline of the overlapping spectrum sharing for multi-user CR systems is presented. The outcome of this paper is very useful to enhance CR systems. Also, it can be easily implemented in practice for spectrum sharing. The users can realize by themselves whether their positions are in the available area or not.

Keywords: Cognitive radio, MIMO, Spectrum sharing, Multi-user communication

Introduction

After the spectrum sensing process, a CR system can identify whether channel under examination is available or occupied by the primary user (PU). If a channel is available, a secondary user (SU) can operate the non-overlapping spectrum sharing, hence interference will only appear within the SUs due to themselves. Alternatively, if a channel is occupied, the SU will operate with overlapping spectrum sharing, in which the interference from each SU will affect the PU and each SU will cause interference to the PU as well. There have been many reported studies in the literature that propose interference reduction methods [1-2]. Some studies [3-4] introduced performance analysis of the transmitted power constraint in spectrum sharing with a transmission antenna selection technique at the secondary transmitter (ST) and a maximum ratio combination technique at the secondary receiver (SR). It was found that the interference level can be up to the transmitted power of each user in the system. Several studies have focused on power control of the SU. In [5-8], researchers developed power allocation schemes to support multi-user CR systems. However, the existing works have only discussed the defined power term, which is not changed by distances or positions. Especially in [3-4], researchers assumed the powers of both interference and users were constant throughout their equations and experiments. This may be a considerable problem in practice because only a few limited areas exhibit such behavior. In fact, the PU and SUs operate by roaming in areas around the base station (BS) and fusion center (FC). So, most areas experience outages due to the specific conditions of assumed powers. This can occur even though effective adaptive power allocation is employed. However, there are some positions that do not produce outages for SUs. If SUs can realize the available area to operate with spectrum sharing, it will provide many benefits to the system. So far, there has not been any work that presents a performance analysis in multi-user CR systems based on position information.

In this paper, the authors have taken into account the effect of the positions of the BS, PU, FCs, and SUs into the performance analysis for spectrum sharing and proposed a spectrum allocation scheme for multi-user MIMO CR systems. The simulation results show that the signal quality in terms of the bit error rate (BER), which can be used with position information in both downlink and uplink operations. Then, the intersection result from the performance analysis on downlink and uplink can avoid the negative impacts to multi-user communications. Finally, the spectrum allocation scheme can allocate the proper frequency for each SU in an entire system to enable good self-evaluation guidelines for overlapping spectrum sharing in multi-user CR systems.

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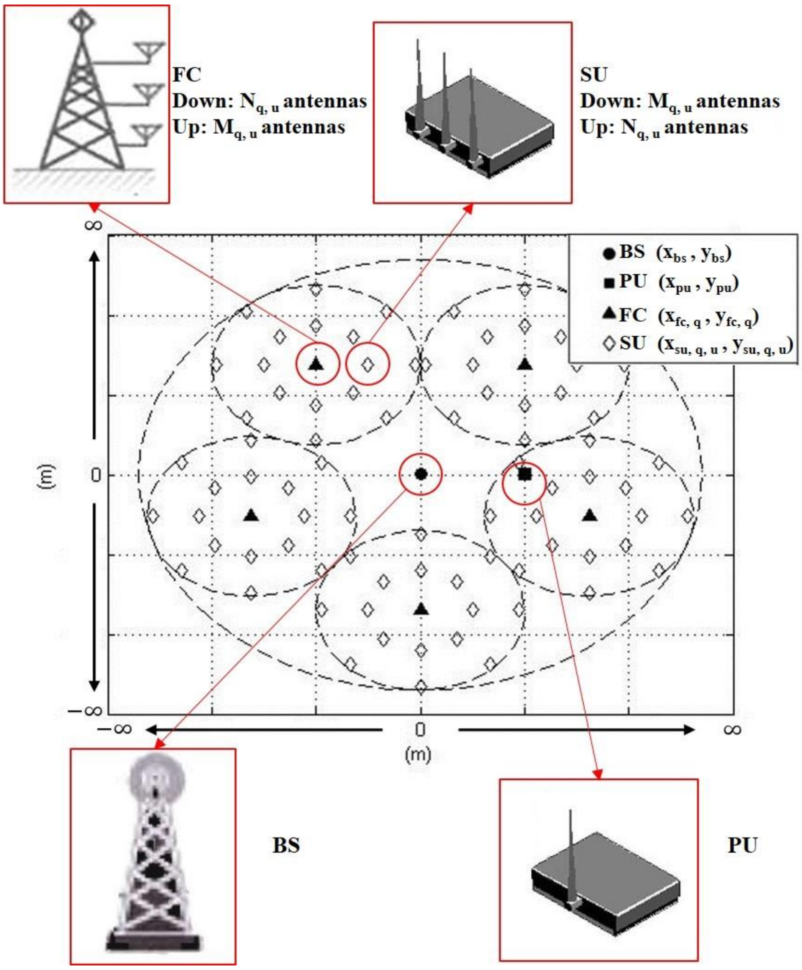

Figure 1 Multi-user spectrum sharing CR system model

2. Materials and methods

2.1 System model

The primary link was composed of only one antenna for both the primary transmitter (PT) and primary receiver (PR). Whereas, each secondary link has a ST and SR, which is equipped with $N_{q,u}$ and $M_{q,u}$ antennas, respectively. The number of transmit and receive antennas are according to each SU from the overall U_q number of SUs in each coverage area of q^{th} FC, as seen in Figure 1. The channel was modeled as flat fading and Rayleigh distributed. It can be seen that the number of antennas of each SU is not necessarily the same, but not less than two antennas is required 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 the q^{th} FC and the antennas of u^{th} SU in its coverage area has a channel coefficient of $h_{ss,q,u}$. The channel between the antennas of the q^{th} FC and an antenna of PU has a channel coefficient of $h_{sp,q}$. The channel between an antenna of BS and the antennas of the u^{th} SU in the coverage area of the q^{th} FC has a channel coefficient of $h_{ps,q,u}$. The channel between the antennas of FC in other coverage areas and the antennas of the u^{th} SU in the coverage area of the q^{th} FC has an average channel coefficient of $\bar{h}_{is,q,u}$, which is the channel between the interference FC and the SU under consideration.

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 the u^{th} SU and the antennas of its q^{th} FC has a channel coefficient of $h_{ss,q,u}$. Also, the channel between the antennas of the u^{th} SU in the coverage area of the q^{th} FC and an antenna of BS has a channel coefficient of $h_{sp,q,u}$. The channel between an antenna of PU and the antennas of the q^{th} FC has a channel coefficient of $h_{ps,q}$, while the channel between the antennas of other SUs in the system and the antennas of the q^{th} FC has an average channel coefficient of $\bar{h}_{is,q,u}$.

Focusing on the node positions under consideration, the distance and power equations are written as follows.

The distance between PT and PR is:

$$R_p = \left(\left(y_{pu} - y_{bs} \right)^2 + \left(x_{pu} - x_{bs} \right)^2 \right)^{\frac{1}{2}}. \tag{1}$$

Hence, the received power of the primary link for both downlink and uplink are given by:

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

where P_{max} is maximum primary output power, λ is wavelength, G_t and G_r are transmitter and receiver gains, respectively.

For the downlink, the distances from PT to SR and from ST to SR, respectively, are:

$$D_{ps,q,u\_d} = \left(\left(y_{su,q,u} - y_{bs} \right)^2 + \left(x_{su,q,u} - x_{bs} \right)^2 \right)^{\frac{1}{2}}, \quad (3)$$

$$D_{ss,q,u\_d} = \left(\left(y_{su,q,u} - y_{fc,q} \right)^2 + \left(x_{su,q,u} - x_{fc,q} \right)^2 \right)^{\frac{1}{2}}, \quad (4)$$

for $q = 1, 2, \ldots, Q$ and Q is the number of FCs. Then, the received power from PT to SR for a downlink is expressed as:

$$P_{ps,q,u\_d} = P_{max} \left(\frac{\lambda}{4\pi D_{ps,q,u\_d}} \right)^2 G_t G_r. \quad (5)$$

The received power from ST to SR for a downlink is expressed as:

$$P_{ss,q,u\_d} = P_{smax} \left(\frac{\lambda}{4\pi D_{ss,q,u\_d}} \right)^2 G_t G_r, \quad (6)$$

where P_{smax} is maximum secondary output power. For the downlink, all FCs are transmitters and they interfere with each other. When we are considering a single transmitter, the interference power matrix due to the nearby FCs can be found from:

$$D_{ssI,q,v,u\_d} = \left(\left(y_{su,q,u} - y_{fc,v} \right)^2 + \left(x_{su,q,u} - x_{fc,v} \right)^2 \right)^{\frac{1}{2}}, \quad (7)$$

for $v = 1, 2, \ldots, V$, and $V = Q$, which is defined as an index for finding the interference power from all FC-SU links. Then the downlink interference distance matrix is:

$$\mathbf{D}_{ssI,q\_d} = \begin{bmatrix} \left[\mathbf{D}_{ssI,q,1\_d} \right]_{1\times U_q} \\ \left[\mathbf{D}_{ssI,q,2\_d} \right]_{1\times U_q} \\ \vdots \\ \left[\mathbf{D}_{ssI,q,q\_d} \right]_{1\times U_q} = \left[\infty \right]_{1\times U_q};\ \text{at } v = q \\ \vdots \\ \left[\mathbf{D}_{ssI,q,V\_d} \right]_{1\times U_q} \end{bmatrix}, \quad (8)$$

where $D_{ssI,q,v,u\_d} \in \mathbf{D}_{ssI,q,v\_d}$. When $v = q$, we are considering the links between a specific FC and all SUs in its coverage area. At this point, the interference distances can be assumed very far until there is almost no interference power. Hence, the interference power matrix is:

$$\mathbf{P}_{ssI,q\_d} = P_{smax} \left(\frac{\lambda}{4\pi \mathbf{D}_{ssI,q\_d}} \right)^2 G_t G_r = \begin{bmatrix} \mathbf{P}_{ssI,q,1\_d} \\ \mathbf{P}_{ssI,q,2\_d} \\ \vdots \\ [0]_{1\times U_q};\ \text{at } v = q \\ \vdots \\ \mathbf{P}_{ssI,q,V\_d} \end{bmatrix}, \quad (9)$$

where $P_{ssI,q,v,u\_d} \in \mathbf{P}_{ssI,q,v\_d}$.

For an uplink, the distances from PT to SR and from ST to SR, respectively, are:

$$D_{ps,q\_u} = \left(\left(y_{fc,q} - y_{pu} \right)^2 + \left(x_{fc,q} - x_{pu} \right)^2 \right)^{\frac{1}{2}}, \quad (10)$$

$$D_{ss,q,u\_u} = \left(\left(y_{fc,q} - y_{su,q,u} \right)^2 + \left(x_{fc,q} - x_{su,q,u} \right)^2 \right)^{\frac{1}{2}}. \quad (11)$$

The received power from PT to SR for an uplink is expressed as:

$$P_{ps,q\_u} = P_{max} \left(\frac{\lambda}{4\pi D_{ps,q\_u}} \right)^2 G_t G_r. \quad (12)$$

The received power from ST to SR for uplink is expressed as:

$$P_{ss,q,u\_u} = P_{smax} \left(\frac{\lambda}{4\pi D_{ss,q,u\_u}} \right)^2 G_t G_r. \quad (13)$$

For the uplink, all SUs are transmitters and they interfere with each other in both the same and various other coverage areas of picocells. When we are considering one of them, the interference power matrix due to SUs in the coverage area of the other nearby FCs can be found from:

$$D_{ssI,q,v,u\_u} = \left(\left(y_{fc,v} - y_{su,q,u} \right)^2 + \left(x_{fc,v} - x_{su,q,u} \right)^2 \right)^{\frac{1}{2}}. \quad (14)$$

So, the uplink interference distance matrix is:

$$\mathbf{D}_{ssI,q\_u} = \begin{bmatrix} \left[\mathbf{D}_{ssI,q,1\_u} \right]_{1\times U_q} \\ \left[\mathbf{D}_{ssI,q,2\_u} \right]_{1\times U_q} \\ \vdots \\ \left[\mathbf{D}_{ssI,q,q\_u} \right]_{1\times U_q} = \left[\infty \right]_{1\times U_q};\ \text{at } v = q \\ \vdots \\ \left[\mathbf{D}_{ssI,q,V\_u} \right]_{1\times U_q} \end{bmatrix}. \quad (15)$$

When $v = q$, we define the interference distances as infinity to find the interference power from other SUs outside the considered coverage area. Hence, the interference power matrix is:

$$\mathbf{P}_{ssI,q\_u} = P_{smax}\left(\frac{\lambda}{4\pi\mathbf{D}_{ssI,q\_u}}\right)^2 G_t G_r = \begin{bmatrix} \mathbf{P}_{ssI,q,1\_u} \\ \mathbf{P}_{ssI,q,2\_u} \\ \vdots \\ [0]_{1\times U_q};\ \text{at } v=q \\ \vdots \\ \mathbf{P}_{ssI,q,V\_u} \end{bmatrix}, \quad (16)$$

where $P_{ssI,q,v,u\_u} \in \mathbf{P}_{ssI,q,v\_u}$. The interference power matrix due to other SUs in the same coverage area is defined as:

$$\mathbf{P}'_{ssII,q\_u} = \mathbf{P}'_{ss,q\_u} - \begin{bmatrix} 0 & \cdots & P_{ss,q,u\_u} & 0 & \cdots & 0 \end{bmatrix}, \quad (17)$$

where $P_{ss,q,u\_u} \in \mathbf{P}_{ss,q\_u}$. In order to find the interference power, we have to remove the power value of the considered SUs from the normally received power matrix found from Equation (13). Hence, the remaining values in the matrix are the interference due to each ST-SR link in the same coverage area of an SU under consideration.

2.2 Performance analysis

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

$$P_{sp} = \left(\frac{-1.5P_pG_c}{(m-1)\ln\left(5BER_p\right)} - N_o\right)\frac{1}{\bar{g}_{sp}}, \quad (18)$$

where G_c is the coding gain [9, Eq. 9.38], N_o is the power spectral density of the noise assumed to be constant and the same for all states, and $\bar{g}_{sp} = av\ g\left(\left|\mathbf{h}_{sp}\right|^2\right)$ is an average channel gain from ST-PR. Considering the power from Equation (18), we can find the BER region of a primary network due to interference from ST in the same location using:

$$D_{sp} = \frac{\lambda}{4\pi}\left(\frac{P_{smax}G_tG_r}{P_{sp}}\right)^{\frac{1}{2}}. \quad (19)$$

With PR as a reference point, the distance from ST to PR D_{sp} from Equation (19) shows the possible position of ST which can be available to communicate with FC around PR. Hence, we can satisfactorily predict the positions of ST that affect PR.

Referring to the power equations of Section 2, the SNR from ST-SR for both downlink and uplink are defined as:

$$\gamma_{ss,q,u} = g_{ss,q,u}\frac{P_{ss,q,u}}{N_0}, \quad (20)$$

where $g_{ss,q,u} = \left|h_{ss,q,u}\right|^2$ is the channel gain from ST-SR, in which $P_{ss,q,u}$ is also dependent on whether it is downlinked as in Equation (6) or uplinked as in Equation (13). Additionally, the SNR from all sources of interference to the considered SR for the downlink is:

$$\gamma_{is,q,u\_d} = g_{ps,q,u}\frac{P_{ps,q,u\_d}}{N_0} + \bar{g}_{is,q,u}\sum_{v=1}^{V}\frac{P_{ssI,q,v,u\_d}}{N_0}, \quad (21)$$

where $g_{ps,q,u} = \left|h_{ps,q,u}\right|^2$ is the channel gain from PT-SR on the downlink, and $\bar{g}_{is,q,u} = \left|\bar{h}_{is,q,u}\right|^2$ is an average channel gain from the interference FC to SU under consideration. For the uplink:

$$\gamma_{is,q,u\_u} = g_{ps,q}\frac{P_{ps,q\_u}}{N_0} + \bar{g}_{is,q,u}\left(\sum_{v=1}^{V}\sum_{u=1}^{U}\frac{P_{ssI,q,v,u\_u}}{N_0} + \sum_{u=1}^{U}\frac{P_{ssII,q,u\_u}}{N_0}\right), \quad (22)$$

where $g_{ps,q} = \left|h_{ps,q}\right|^2$ is the channel gain from PT-SR on the uplink, and $\bar{g}_{is,q,u} = \left|\bar{h}_{is,q,u}\right|^2$ is an average channel gain from other SUs in the system to the FC under consideration.

The Cumulative Distributed Function (CDF) of the channel gain g_{ss} [4, Eq. 5] is given by:

$$F_{g_{ss,q,u}}(x) = \frac{1}{\Gamma\left(M_{q,u}+1\right)}\left[\left(\frac{x}{g_{ss,q,u}}\right)^{M_{q,u}N_{q,u}}\Gamma\left(1-M_{q,u}\left(N_{q,u}-1\right),\frac{x}{g_{ss,q,u}}\right) + \gamma\left(M_{q,u}+1,\frac{x}{g_{ss,q,u}}\right)\right], \quad (23)$$

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

The BER of overlapping spectrum sharing for downlink and uplink can be expressed as:

$$BER_{Int,q,u}(a,b) = \frac{a}{2}\sqrt{\frac{b}{2\pi}}\int_0^\infty\frac{e^{-\frac{b}{2}x}}{\sqrt{x}}\int_0^\infty\frac{e^{-\frac{y}{\gamma_{is,q,u}}}}{\gamma_{is,q,u}}F_{g_{ss},q,u}\left(\frac{x(y+1)}{\frac{P_{ss,q,u}}{N_0}}\right)dydx, \quad (24)$$

where a and b are modulation-specific constants, such as $(a,b) = (1, 2)$ for BPSK, $(a,b) = (1, 1)$ for BFSK, and $(a,b) = (2(m\text{-}1)/m, 6\log_2(m)/(m^2-1))$ for m − PAM. Equation (24) can be proved by starting with:

$$F_{g_{ss},q,u}\left(\frac{x(y+1)}{\frac{P_{ss,q,u}}{N_0}}\right) = \frac{1}{\Gamma\left(M_{q,u}+1\right)}\left[\left(\frac{x}{\gamma_{ss,q,u}}\right)^{M_{q,u}N_{q,u}}\Gamma\left(1-M_{q,u}\left(N_{,u}-1\right),\frac{x(y+1)}{\gamma_{ss,q,u}}\right)\times(y+1)^{M_{q,u}N_{q,u}} + \gamma\left(M_{q,u}+1,\frac{x(y+1)}{\gamma_{ss,q,u}}\right)\right]. \quad (25)$$

Then,

$$F_{\gamma_{int}}(x)=\int_0^\infty \frac{e^{-\frac{y}{\gamma_{is,q,u}}}}{\gamma_{is,q,u}}F_{g_{ss},q,u}\left(\frac{x(y+1)}{\frac{P_{ss,q,u}}{N_0}}\right)dy. \quad (26)$$

Using [10, Eq. 8.352.5], [10, Eq. 8.352.4], [10, Eq. 3.352.1], then:

$$\begin{aligned}F_{\gamma_{int}}(x)&=A\Gamma\left(M_{q,u}N_{q,u}+1,\frac{1}{\gamma_{is,q,u}}\right)x^{M_{q,u}N_{q,u}}\mathrm{Ei}\left(-\frac{x}{\gamma_{ss,q,u}}\right)+A\left(M_{q,u}N_{q,u}\right)!\\&\times\sum_{k=1}^{M_{q,u}N_{q,u}}\left(\frac{1}{\gamma_{is,q,u}}\right)^{k}\frac{1}{k!}x^{M_{q,u}N_{q,u}}\left(\frac{1}{\gamma_{is,q,u}}+\frac{x}{\gamma_{ss,q,u}}\right)^{-k}\Gamma\left(k,\left(\frac{1}{\gamma_{is,q,u}}+\frac{x}{\gamma_{ss,q,u}}\right)\right)\\&+B\left(\frac{x}{\gamma_{ss,q,u}}\right)^{M_{q,u}N_{q,u}-k-1}\left(\frac{1}{\gamma_{is,q,u}}+\frac{x}{\gamma_{ss,q,u}}\right)^{k-M_{q,u}N_{q,u}}\\&\times\Gamma\left(M_{q,u}N_{q,u}-k,\left(\frac{1}{\gamma_{is,q,u}}+\frac{x}{\gamma_{ss,q,u}}\right)\right)\\&+C\left[1-\left(\frac{1}{\gamma_{is,q,u}}\right)e^{\frac{1}{\gamma_{is,q,u}}}\sum_{k=0}^{M_{q,u}}\left(\frac{x}{\gamma_{ss,q,u}}\right)^{k}\left(\frac{1}{\gamma_{is,q,u}}+\frac{x}{\gamma_{ss,q,u}}\right)^{-k-1}\right.\\&\left.\times\frac{1}{k!}\Gamma\left(k+1,\left(\frac{1}{\gamma_{is,q,u}}+\frac{x}{\gamma_{ss,q,u}}\right)\right)\right].\end{aligned} \quad (27)$$

Define $A=\frac{(-1)^{M_{q,u}(N_{q,u}-1)}e^{\frac{1}{\gamma_{is,q,u}}}\left(\frac{\gamma_{is,q,u}}{\gamma_{ss,q,u}}\right)^{M_{q,u}N_{q,u}}}{\Gamma\left(M_{q,u}+1\right)\left(M_{q,u}\left(N_{q,u}-1\right)-1\right)!}$,

$B=\frac{\left(\frac{1}{\gamma_{is,q,u}}\right)}{\Gamma\left(M_{q,u}+1\right)\left(M_{q,u}\left(N_{q,u}-1\right)-1\right)!}e^{\frac{1}{\gamma_{is,q,u}}}\sum_{k=0}^{M_{q,u}\left(N_{q,u}-1\right)-2}k!(-1)^{M_{q,u}\left(N_{,u}-1\right)+k}$,

and $C=\frac{M_{q,u}!}{\Gamma\left(M_{q,u}+1\right)}$, then equation (27) is substituted into equation (24). Using [10, Eq. 6.228.2], [10, Eq. 3.383.4], [10, Eq. 3.383.5], and [10, Eq. 3.352.2] to get:

$$\begin{aligned}BER_{Int,q,u}(a,b)&=\frac{a}{2}\sqrt{\frac{b}{2\pi}}\frac{1}{\Gamma\left(M_{q,u}+1\right)}\left[\frac{(-1)^{M_{q,u}\left(N_{q,u}-1\right)+1}e^{\frac{1}{\gamma_{is,q,u}}}}{\left(M_{q,u}\left(N_{q,u}-1\right)-1\right)!}\right.\\&\left(\frac{\gamma_{is,q,u}}{\gamma_{ss,q,u}}\right)^{M_{q,u}N_{q,u}}\times\frac{\Gamma\left(M_{q,u}N_{q,u}+1,\frac{1}{\gamma_{is,q,u}}\right)}{\left(M_{q,u}N_{q,u}+\frac{1}{2}\right)}\frac{\Gamma\left(M_{q,u}N_{q,u}+\frac{1}{2}\right)}{\left(\frac{1}{\gamma_{ss,q,u}}+\frac{b}{2}\right)^{M_{q,u}N_{q,u}+\frac{1}{2}}}\\&\times{}_2F_1\left(1,M_{q,u}N_{q,u}+\frac{1}{2};M_{q,u}N_{q,u}+\frac{3}{2};\frac{b\gamma_{ss,q,u}}{2+b\gamma_{ss,q,u}}\right)+(-1)^{M_{q,u}\left(N_{q,u}-1\right)}\\&\times\left(M_{q,u}N_{q,u}\right)!\Gamma\left(M_{q,u}N_{q,u}+\frac{1}{2}\right)e^{\frac{b\gamma_{ss,q,u}+2}{4\gamma_{is,q,u}}}\sum_{k=1}^{M_{q,u}N_{q,u}}\frac{(k-1)!}{k!}\sum_{m=0}^{k-1}\frac{\left(\frac{1}{\gamma_{is,q,u}}\right)^{m}}{m!}\\&\times\left(\frac{1}{\gamma_{ss,q,u}}+\frac{b}{2}\right)^{-\frac{1}{2}\left(M_{q,u}N_{q,u}+m-k+\frac{3}{2}\right)}\left(\frac{\gamma_{ss,q,u}}{\gamma_{is,q,u}}\right)^{\frac{1}{4}\left(2k+2m-2M_{q,u}N_{q,u}-1\right)}\\&\times W_{\frac{1}{2}\left(m-k-M_{q,u}N_{q,u}-\frac{1}{2}\right),-\frac{1}{2}\left(M_{q,u}N_{q,u}+m-k+\frac{1}{2}\right)}\left(\frac{b\gamma_{ss,q,u}+2}{2\gamma_{is,q,u}}\right)+\left(\frac{1}{\gamma_{is,q,u}}\right)\\&\times e^{\frac{b\gamma_{ss,q,u}+2}{4\gamma_{is,q,u}}}\sum_{k=0}^{M_{q,u}\left(N_{q,u}-1\right)-2}(-1)^{M_{q,u}\left(N_{q,u}-1\right)+k}k!\left(M_{q,u}N_{q,u}-k-1\right)!\\&\times\Gamma\left(M_{q,u}N_{q,u}-k-\frac{1}{2}\right)\sum_{m=0}^{M_{q,u}N_{q,u}-k-1}\frac{\gamma_{ss,q,u}^{1-m}}{m!}\left(\frac{1}{\gamma_{ss,q,u}}+\frac{b}{2}\right)^{-\frac{1}{2}\left(m+\frac{1}{2}\right)}\\&\left(\frac{\gamma_{ss,q,u}}{\gamma_{is,q,u}}\right)^{\frac{1}{2}\left(m-\frac{3}{2}\right)}\times W_{\frac{1}{2}\left(2k-2M_{q,u}N_{q,u}+m+\frac{3}{2}\right),\frac{1}{2}\left(-m+\frac{1}{2}\right)}\\&\left(\frac{b\gamma_{ss,q,u}+2}{2\gamma_{is,q,u}}\right)+M_{q,u}!\times\left[\sqrt{\frac{2\pi}{b}}-\left(\frac{1}{\gamma_{is,q,u}}\right)e^{\frac{b\gamma_{ss,q,u}+2}{4\gamma_{is,q,u}}}\right.\\&\sum_{k=0}^{M_{q,u}}\Gamma\left(k+\frac{1}{2}\right)\sum_{m=0}^{k}\frac{\gamma_{ss,q,u}^{-m+1}}{m!}\left(\frac{1}{\gamma_{ss,q,u}}+\frac{b}{2}\right)^{-\frac{1}{2}\left(m+\frac{1}{2}\right)}\\&\left.\left.\times\left(\frac{\gamma_{ss,q,u}}{\gamma_{is,q,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,q,u}+2}{2\gamma_{is,q,u}}\right)\right]\right],\end{aligned} \quad (28)$$

where ${}_2F_1(.,.;.;.)$ is the hypergeometric function and $W_{\varepsilon,\mu}(.)$ is the Whittaker W-function.

2.3 GPS error

Although GPS devices have been developed to be more accurate, there are still some errors that cannot be ignored in an overlapping spectrum sharing process. All position errors clearly affected the SUs' decision. So, we can add the GPS errors into the performance analysis using Equations (29) and (30) to replace the distance equations of Section 2.1.

$$\hat{\mathbf{x}}_{su}=\mathbf{x}_{su}\pm\mathbf{rand}\left[0,error_{GPS}\right]_{U\times Q}\cos\left(\tan^{-1}\left(\frac{\mathbf{y}_{su}}{\mathbf{x}_{su}}\right)\right), \quad (29)$$

$$\hat{\mathbf{y}}_{su}=\mathbf{y}_{su}\pm\mathbf{rand}\left[0,error_{GPS}\right]_{U\times Q}\sin\left(\tan^{-1}\left(\frac{\mathbf{y}_{su}}{\mathbf{x}_{su}}\right)\right), \quad (30)$$

where the GPS errors are random between 0 and $error_{GPS}$, where the $error_{GPS}$ value is the accuracy limit of each GPS device.

2.4 Spectrum allocation scheme

The final process of in a CR system is the spectrum decision that chooses the proper frequency channel for the needs of users. This spectrum allocation scheme arranges the proper frequency for each SU in the entire system. A schematic diagram of this concept is presented in Figure 2 that shows the following steps.

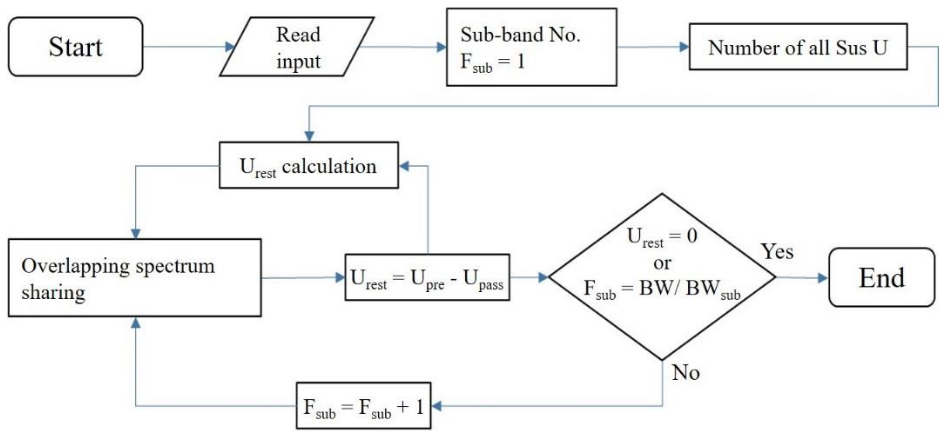

Figure 2 Full-system overlapping spectrum sharing flowchart

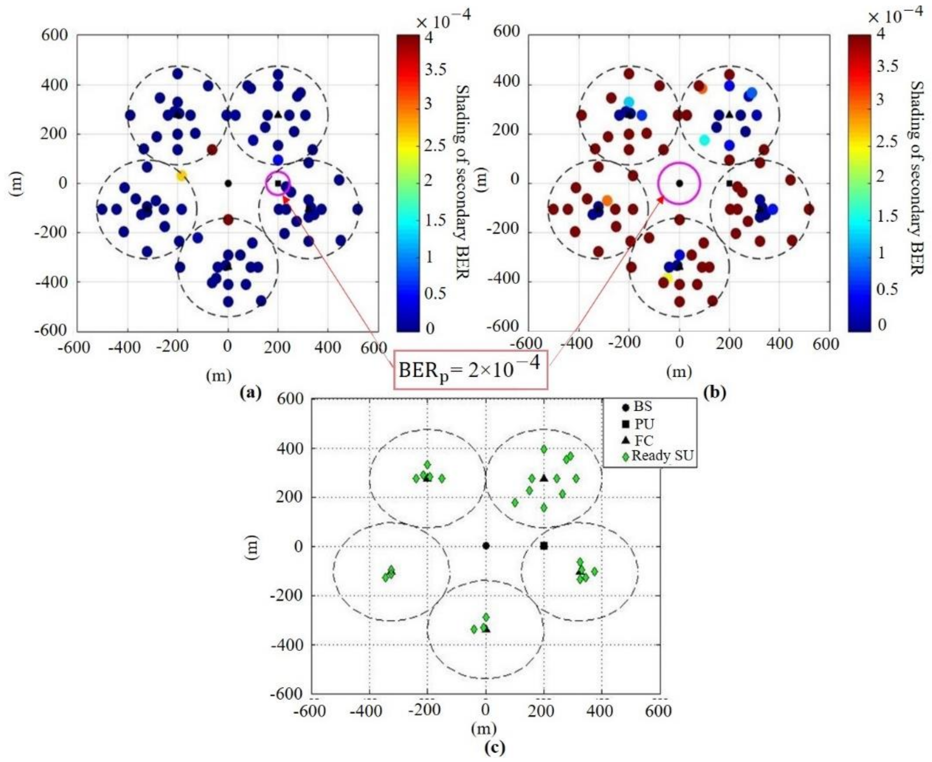

Figure 3 Overlapping spectrum sharing for a multi-user multi-cell CR system ignoring GPS error on (a) downlink and (b) uplink, and (c) the intersection result between downlink and uplink

Step 1: After the spectrum sensing process, the spectrum allocation process starts by analyzing the first channel, where the number of considered channels is equal to bandwidth value divided by a sub-bandwidth value. Hence, the considered frequency channel $F_{sub} = 1, 2, \ldots, BW/BW_{sub}$, in which the BW and BW_{sub} values are defined based on specific communication standards, and F_{sub} is the sub-band number.

Step 2: The number of all SUs and each of their positions are subjected to the performance analysis process. The proper SU is an SU that passes the BER condition on both downlink and uplink in a considered round. Hence, the result of this process is the number of SUs that are appropriate for communication.

Step 3: In order to know whether the spectrum allocation process has been completed or not, we have to find the remaining SUs that have not yet passed. The remaining SUs from the previous round can be calculated as:

$$U_{rest} = U_{pre} - U_{pass}, \tag{31}$$

where U_{rest} is the number of SUs that have not passed in the round under consideration, U_{pre} is the number of SUs in the previous round, and U_{pass} is the number of SUs that have already passed the BER condition in the current round. In the first round, U_{rest} is equal to the total number of all SUs.

Then, steps 2 and 3 will be repeated until the all SUs are capable of communication or the process comes to the last round, such that $F_{sub} = BW/BW_{sub}$. If the process comes to the last round and $U_{rest} \neq 0$, the remaining SUs will be unable to operate at that time.

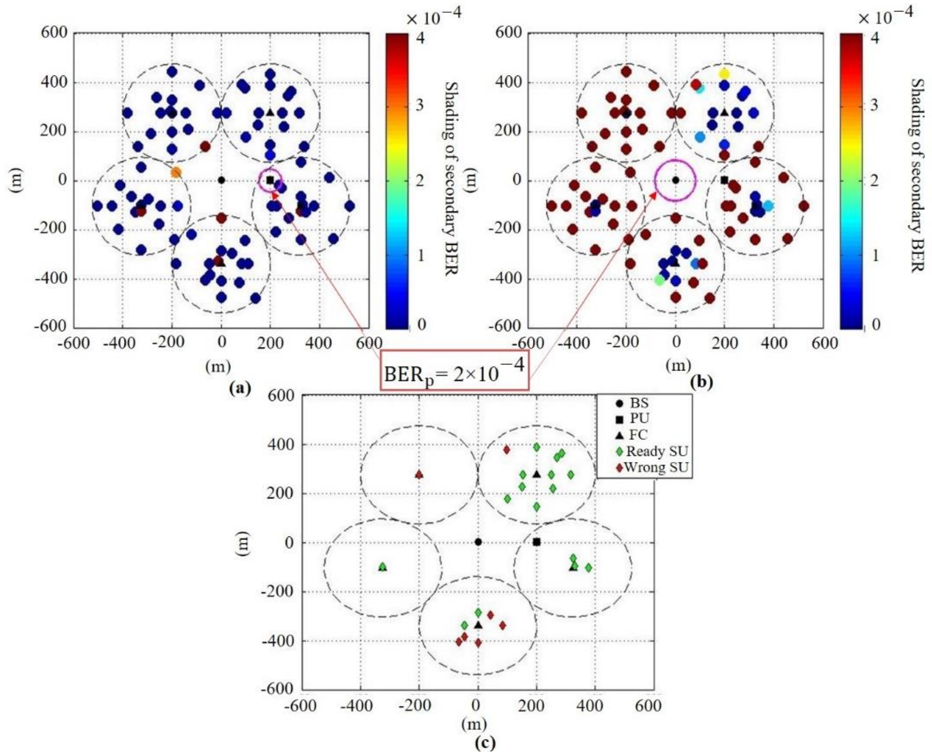

Figure 4 Overlapping spectrum sharing for a multi-user multi-cell CR system by adding a 10 m GPS error on (a) downlink and (b) uplink, and (c) the intersection result between downlink and uplink

Step 4: The new term of spectrum sharing has to wait for the next observation time of spectrum sensing.

3. Simulation results and discussions

MATLAB was employed for the simulations of the current study. The channel model simulations are based on the LTE standard [11], which defines the system parameters including its frequency, 1920 MHz - 1980 MHz for the uplink operating band, 2110 MHz - 2170 MHz for the downlink operating band, 23 dBm for the maximum transmitted power, -103.535 dBm for minimum received power, with a tolerated BER $= 2\times10^{-4}$. In this work, the authors defined $(a,b) = (1,2), G_t = 0\ dB, G_r = 6\ dB, G_c = 6\ dB, m = 16,$ 0 dBm for a transmitted power of BS, $N_{q,u}$ and $M_{q,u}$ are random from 2 to 4 antennas. There is a PU per one frequency channel that randomly appears inside a macrocell. There are 5 FCs (5 picocells) and 16 SUs per one coverage area of FC in which the SUs randomly reside.

Figure 3 shows an ideal case that ignores GPS error. Figures 3a and 3b show the BER results of SUs for downlink and uplink, respectively. For the downlink in Figure 3a, there is a circle around the PU that was predicted by defining $BER_p = 2\times10^{-4}$, according to Equation (19). This prediction circle exists to assist the PU to function normally so that the FC stays inside the circle. Since FCs cannot change their position, when PU appears too close to any FC, that FC has to access other frequency channels. This has to occur in a non-overlapping mode to avoid undesirable interference in the primary link. As can be seen from this figure, some SUs have BER values that are more than 2×10^{-4} due to the interference from BS which are inappropriate for communication on this spectrum. Apart from these SUs, others in different positions are available to operate MIMO CR communications. For the uplink in Figure 3b, if SUs stay inside the circle that is defined by $BER_p = 2\times10^{-4}$, they cannot operate with spectrum sharing in order to protect the normal function of the BS. Some SUs have a BER of more than 2×10^{-4} due to interference from PU and other nearby SUs. Hence, those SUs cannot operate with spectrum sharing in this frequency channel. Finally, the intersection results of available SUs between Figure 3a and Figure 3b is shown in Figure 3c. It is observed that some SUs can successfully perform with an overlapping spectrum under both downlink and uplink operations. This is based on each SU's position under the condition that the BER of PU will be less than 2×10^{-4}.

With the same node positions and number of antenna elements of each node member as in Figure 3, the authors enhanced the GPS error by 0-10 m in Figure 4 [12]. Figures 4a and 4b show the BER results of SUs for downlink and uplink operations, respectively. If the GPS error for most of the node positions increases and the distance between interference nodes and SR is sufficient, the system may obtain an incorrect result. The BER of an SU under consideration can demonstrated that it passes the condition although it shouldn't pass when the calculated BER is less than it should be. This may cause a communication malfunction in other nodes in the system. Alternatively, if the GPS error for most node positions decreases and the distance between interference nodes and SR is sufficient, it may cause a false alarm because the calculated BER exceeds its allowed value. This may reduce the number of SUs that pass. From the same operation as shown in Figure 3, the intersection result of available SUs between Figure 4a and Figure 4b is shown in Figure 4c. When compared to Figure 3c, it is clearly seen that some SUs that should not pass in Figure 3c appear in this figure. The authors have defined the incorrect SUs with red marks. Moreover, some SUs that should pass disappear.

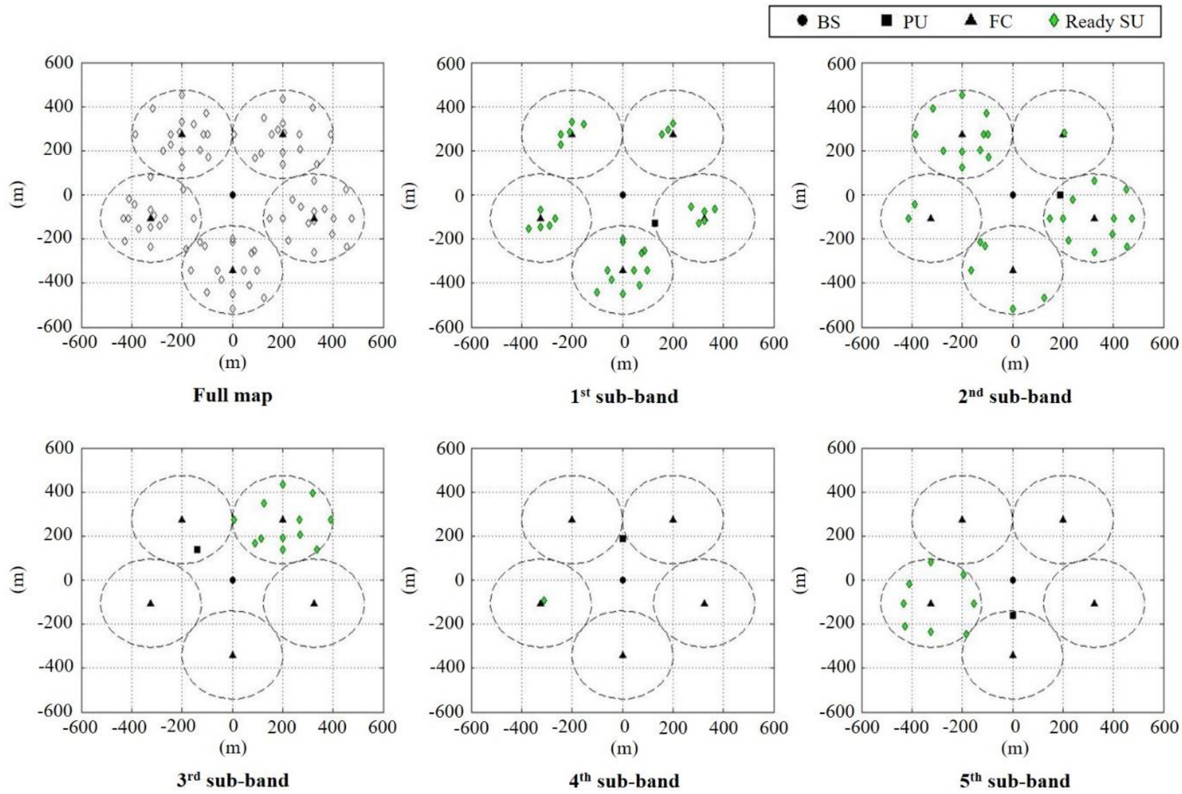

Figure 5 Full-system overlapping spectrum sharing with 16 users per a picocell

In order to achieve the end of an operation, all of the processes in Figure 2 must operate, as is shown in Figure 5. The authors defined each picocell as having 16 randomly positioned SUs. PUs in all frequency channels have random positions and $BW_{sub} = 5$ MHz. Hence, the number of sub-bandwidths is 12. Starting in the top left of the figure, the full map of the CR system is seen representing all of node member positions except the PU since the PU of each frequency channel has a different position. Thus, the PU appears in next figure. As in Figure 4, after the performance analysis process of 1st sub-bandwidth has been performed, the result is shown in the top center figure. The proper SUs have achieved permission first, causing reduction in the interference factor at the next sub-bandwidth. As seen in the bottom center figure, there is only one SU passing the BER condition because it is an influential point affecting other SUs causing them to fail. So, in the next sub-bandwidth, many of the remaining SUs achieve this goal. Normally, the operation has to be finished within 12 sub-bandwidths for the LTE because $BW = 60$ MHz and $BW_{sub} = 5$ MHz. However, in this simulation, all SUs were achieve within 5 sub-bandwidths. It is notable that the effect of GPS error in this result exists but is not shown since the system does not know how much impact it has in reality.

4. Conclusions

Position-based performance analysis for overlapping spectrum sharing techniques has been presented in this paper. The mathematical solution shows the relationship between BER and user positions, in which the same frequency users will affect each other, more or less based on their positions. It can be clearly seen in the terms of multi-user systems that if either the distance or direction between the transmitter and receiver vary, then the BER result is definitely different. The simulation results can describe the interference impact of each user in a CR system related to a thorough performance analysis in terms of a BER that supports both downlink and uplink operations. Additionally, the system can allocate frequency channels to all users as thoroughly as possible by employing this spectrum allocation scheme. The results are very useful for multi-user MIMO CR implementation to make decisions on whether the current position of SU is suitable for establishing communication or not.

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