Exploitation of the Channel-bonding Technique to an Adaptive Multiple Input Multiple Output-Orthogonal Frequency Division Multiplexing Based Cognitive Radio System for Throughput Enhancement

Santosh Itraj and Dr. Uttam Bombale
D.O.T. Shivaji University, Kolhapur
E-mail: ssitraj@yahoo.com, uttam_bombale@rediffmail.com

ABSTRACT

Cognitive radio (CR) is the most prominent technology that resolves the conflict between the users’ demands and available resources. It enhances the performance of the wireless communication system by using scarce resources efficiently and intelligently. Channel-bonding is one of the techniques that can be exploited to the CR to provide an extensive boost in the throughput of the system. In most of the existing CR systems, the performance improvement has been achieved through link adaptation by adapting modulation, coding rate, transmission power, Multiple input multiple output (MIMO) profile, etc. The adaptive channel-bonding technique can be incorporated in the CR node to ensure a higher data rate in case of the transmission of the chunk of data. The limitations imposed by the channel-bonding technique can be mitigated to a certain extent by combining this technique with orthogonal frequency division multiplexing (OFDM) technology. MIMO technology and rate adaptation. We propose joint rate and channel-bonding adaptation on a per-packet basis for the MIMO-OFDM based CR system operating in multi-channel and multi-user environment. The channel condition and the soft information about the activities of the primary users are used to define the parameters. The MIMO-OFDM based CR system is designed based on 802.11n protocol and is operated in spatial division multiplexing (SDM) mode. The performance of the proposed CR system is investigated with different channel-bonding probabilities and is compared with the performance of the system without channel-bonding. The proposed CR system supports interweave, underlay, hybrid channel access schemes. The extensive improvement in the throughput of the system has been observed with a joint rate and channel-bonding adaptation scheme. Such systems can be useful in cognitive wireless sensor networks, where bulk data has to be transmitted with minimum delay. The system performance is validated by comparing the throughput of the system with the theoretical performance of the wireless system over Rayleigh channel with rate adaptation.

Keywords: Cognitive radio, MIMO-OFDM, Channel-bonding, Throughput, BER.

1. INTRODUCTION

The next-generation wireless communication systems are expected to have features like higher data rates, multimedia services, high quality of services (QoS), and seamless communication. The exponential growth in wireless communication technology and its applications resulted in overcrowding of the unlicensed bands. However, as per the report from the Federal communication committee, the licensed bands are inefficiently utilized. This results in the scarcity of the spectrum and energy [1]. The cognitive radio technology is the prominent key to resolve the challenges imposed by scarce resources. It optimizes the usage of precious scarce resources. CR is an intelligent device that senses and learns from the RF environment and adapts the system parameters to the dynamic RF environment to optimize the performance of the system. CR technology ensures efficient utilization of the spectrum by allowing unlicensed users (secondary users (SUs)) to use the spectrum owned by licensed users (primary users (PUs)) in an opportunistic way [2]. CR uses the licensed spectrum by following channel access schemes such as interweave, underlay, overlay, and hybrid [3, [4].

The QoS in the CR system can be enhanced with different approaches in spectrum sensing, spectrum detection, spectrum sharing, spectrum mobility, link adaptation, etc [5]. The link adaptation can be used to control the parameters such as modulation, code rate, transmission power, MIMO profile, packet length, channel bandwidth, etc. so as to adapt to dynamic channel conditions. Thus, the performance of the CR system can be improved by exploiting the channel-bonding scheme to the opportunistic channel access environment [6]. The channel-bonding is a technique of combining contiguous non-overlapping channels to form a wide band channel [7]. The basic concept of channel-bonding is illustrated in Fig. 1. It is assumed that the CH1 and CH2 are the two contiguous non-overlapping channels licensed by the primary users PU1, PU2, and having a bandwidth of 20 MHz each. In the cognitive radio environment, SU is allowed to use the licensed channel only in the absence of the PU, i.e., when a channel is idle. Hence, as shown in Figure 1, when both the channels are idle the channel bonding can be used by SU to form a wide band channel of bandwidth 40 MHz causing an enhancement in the throughput of the system. The channel bonding ensures a reduction in the data transmission delay. Otherwise, SU uses the available channel with a bandwidth of 20 MHz. The motive behind the channel-bonding is to increase the throughput of the system and reduce the
proportion time. The channel-bonding has been widely exposed in conventional wireless communication systems [8]. Increasing channel bandwidth may lead to a reduction in transmission range, an increase in the susceptibility to the interference, and an increase in power consumption. However, by integrating MIMO-OFDM technology with adaptive channel-bonding, the system can have a minimal sacrifice to the transmission range and QoS [9]. The exposure of the channel-bonding to the CR network is a challenging task since the consideration has to be given to the number of PUs and SUs in the network, a number of frequency channels, activities of the PUs, spectrum sensing method, application of the system, etc [10]. The research community [9], [11], [12], [13], [14], [15], and [16] have rigorously studied the channel-bonding schemes for traditional non-CR wireless communication systems. The majority of the schemes have been used to improve the throughput of the system. Some have motive to reduce the propagation delay. Some of the proposals have implemented channel width adaptation based on the throughput requirement.

Recently, many researchers have focused on the exposure of channel-bonding techniques to the CR network (CRN) to enhance the performance of the CRN in terms of the throughput, energy consumption, propagation delay, etc. This is possible by exploiting adaptive channel-bonding and OSA in CR in a complementary manner with each other. The channel-bonding scheme can be beneficial in applications such as wireless sensor networks, cellular networks with cognitive capability and have to transmit a chunk of data at high speed and with minimal delay. The limitation on the range of coverage because of the increased channel bandwidth can be overcome by using co-operative relay CR networks.

The authors in [17] have proposed the channel-bonding scheme for the secondary user to increase the transmission rate. In this case, SUs are allowed to sense the multiple channels in a slot and apply the channel-bonding after detecting the consecutive idle channels. The conditions under which the channel-bonding scheme is beneficial for the OSA network have been investigated in [18]. The authors have proposed the analytical framework for investigating the average throughput of the system. It has been shown that the extent of the benefits depends upon the OSA network features such as the total number of channels available for bonding, network size, etc. The primary user activity awareness channel-bonding algorithm has been proposed in [19]. Reduction in the interference to the PUs has been observed through the intelligent channel-bonding scheme. It has also ensured effective spectrum utilization.

The dynamic spectrum handoff scheme with channel bandwidth adaptation for SU has been proposed and in [20]. In this case, the non-contiguous idle channel-bonding scheme has been considered. The performance of the SU has been investigated in terms of the blocking probability, the forced termination probability, and the throughput. To provide more flexibility in the channel-bonding and improve the spectrum usage efficiency the channel-bonding of the non-contiguous channels can be used. The authors in [21], proposed the noncontiguous channel-bonding scheme using TV white spaces based on the non-contiguous OFDM (NC-OFDM) transmission. It has been observed that better symbol error rate can be obtained with non-contiguous channel-bonding as compared to that of the contiguous channel-bonding scheme. In [22], the authors have investigated the availability of the TV white spaces for CR in Malaysia to identify the maximum and minimum bandwidth available for opportunistic use by CR based on the time and location. This is helpful in developing a dynamic channel-bonding scheme. The channel-bonding can be used to improve the spectrum handoff utilization, which helps in improving the throughput of the CR system [23]. The effect of sensing overhead on the performance of the SUs that use non-contiguous bonding for acquiring spectrum has been investigated in [24]. The system model is based on the Markov chain consisting of multiple PUs and SUs. In addition, the effect of the number of bonded channels on throughput performance has been analyzed. In [25], authors have proposed hybrid channel access mode along with the channel-bonding scheme for the high priority users (PU and SU) to boost the transmission efficiency. The scheme is based on the activities of the PUs. The authors in [26] have investigated the performance of SU with a channel-bonding scheme based on a two-dimensional Markov chain model. The effect of channel-bonding on forced termination probability and the blocking probability has been analyzed. The channel-bonding scheme for PUs and channel reservation scheme for SUs have been proposed in [27]. The performance of CRN is evaluated using a Markov chain model.

The interesting study of exposure of channel-bonding schemes for CRN reveals that it has been considered widely in traditional non-CR networks such as WLAN, wireless sensor networks, cellular networks, etc. It can be realized that channel-bonding is rarely exposed to the CR networks. The majority of the channel-bonding schemes for CR networks are based on PUs activities. In most of the CR systems that are equipped with channel-bonding feature, no technology such as MIMO-OFDM, channel access schemes have been taken into account for mitigating interference, range extension, minimizing energy consumption, etc. to overcome the
limitations of channel-bonding technique. The effect of the channel-bonding is also the function of the factors such as the number of idle channels, number of the CR nodes in the network, geographical area, etc. Hence, it is necessary to adapt the channel bandwidth based on not only activities of PUs but also the instantaneous channel condition (CSI). Motivated by the need and challenges in exploiting the channel-bonding to the CR network we propose the novel joint rate and channel-bonding adaptation scheme for MIMO-OFDM based CR system. The proposed scheme is aware of the activities of PUs and the CSI for the selected channel in the multi-user and multi-channel environment.

The summary of the contributions of this article is

1. We propose the novel joint rate and channel-bonding adaptation controller for multi-user and multi-channel MIMO-OFDM based CR system. The proposed scheme is aware of PUs activities and CSI. The proposed CR system supports interweave, underlay, and hybrid channel access schemes.
2. The proposed algorithm is used to evaluate the performance of the system with variable channel-bonding probabilities in a dynamic channel-switching environment.
3. The performance of the system without channel-bonding is also evaluated to compare with the proposed scheme.
4. The performance of the proposed scheme is compared with the adaptive channel-bonding scheme that considers only the activities of the PUs.

The proposed scheme is developed to optimize the throughput with minimum interference to the nearby channels and users. It has been developed to ensure maximum benefits with minimal adverse effects on the range and energy consumption with less complexity. This is ensured by the integration of the adaptive rate and channel-bonding scheme with MIMO-OFDM technology supporting different channel access schemes in the CR environment.

The paper is organized as follows. In section 2, the system model is described. Section 3 depicts the proposed algorithm for the CR system. The discussion on the simulation results is comprised in section 4. Finally, conclusions are drawn in section 5.

2. SYSTEM MODEL

2.1 System description

The system environment for the proposed MIMO-OFDM based CR system with joint rate and channel-bonding adaptation is illustrated in Fig. 2. It comprises two primary users PU1, PU2, and two secondary users SU1, SU2. It is assumed that the primary users PU1 and PU2 are licensed users of TV spectrum CH1 and CH2 respectively. The random ON-OFF model is used to approximate the activity of the PU1, whereas the status of the PU2 is defined at the time of the simulation. The secondary nodes are (2 × 2) MIMO-OFDM devices based on the 802.11n protocol [28]. In the proposed system SU1 communicates with SU2 over one of the selected channel CH1 or CH2 (c = 2) used independently with band width of CB1 = 20 MHz or bonded channel CHB12 (CH1 + CH2) (c = 3) with band width of CB2 = 40 MHz. It has been assumed that the CH1 and CH2 are two contiguous and non-overlapping channels. The channels used in the environment have Rayleigh distribution. The system design parameters are described in Table 1.

Table 1: System Design Parameters

<table>
<thead>
<tr>
<th>No.</th>
<th>System Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WLAN Standard</td>
<td>HT–CBW20, HT-CBW40 modes</td>
</tr>
<tr>
<td>2</td>
<td>Guard interval</td>
<td>800 ns</td>
</tr>
<tr>
<td>3</td>
<td>PSDU length</td>
<td>1000 bytes</td>
</tr>
<tr>
<td>4</td>
<td>Maximum packet</td>
<td>1.3 ms</td>
</tr>
<tr>
<td></td>
<td>period</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>MIMO mode</td>
<td>(2 × 2) SDM</td>
</tr>
<tr>
<td>6</td>
<td>Targeted BER</td>
<td>10⁻¹</td>
</tr>
<tr>
<td>7</td>
<td>Maximum average</td>
<td>2W,</td>
</tr>
<tr>
<td></td>
<td>transmit power</td>
<td>1W (For underlay mode)</td>
</tr>
</tbody>
</table>

The communication between the secondary users has been supported by different channel access schemes such as an interweave, an underlay, and hybrid (interweave-underlay). It has been assumed that the PU2 has always allowed the SU2 to use CH2, i.e. whether PU2 is absent or present. In the presence of the PU2, SU2 is allowed to use CH2 with constraints on the transmission power so as not to cross the interference threshold defined by PU2. Thus in the presence of the PU2, the channel CH2 is accessed by SU2 in an underlay manner. However, SU2 has assigned higher priority to CH1 and it has been accessed opportunistically. Thus, CH1 is used by SU1 only in the absence of the PU1. When PU1 occupies the CH1, it is vacated by the SU1 to resume the communication over CH2. This defines the interweave channel access scheme. In the proposed system, adaptive channel-bonding is applied in the absence of both primary users (PU1 = 0 and PU2 = 0) along with MCS selection based
on the status of the channel reflected by the CSI. In the presence of any of the PU, the channels CH1 and CH2 are used independently and access scheme is decided by the status of the PUs. In this mode of operation, channels are used without bonding.

The performance of the system is evaluated on a MATLAB simulation platform. The system performance has been evaluated with different channel-bonding probabilities to reflect the effect of the joint channel-bonding and rate adaptation. The performance of the proposed system has been compared with the system performance based on PU activities aware adaptive channel-bonding scheme. The system is validated by comparing the system performance with the results obtained analytically for rate adapted MIMO-OFDM system over Rayleigh channel.

2.2. Mathematical Model

The proposed system comprises the secondary users SU1 and SU2 with two transmit and two receive antennas defined as

\[ N_{tx} = N_{re} = 2 \]  

SU1 communicates with SU2 by using SDM mode supported by 802.11n protocol. It is assumed that the transmission power is equally distributed between the two antennas. The detection of the presence of any of the primary users (PU1 or PU2) forces the system to use the channels CH1 and CH2 independently i.e. without bonding. The channel access scheme is decided by the activities of the PUs. It may be interweave or underlay or hybrid (interweave-underlay). However, in the absence of both the PUs the channels CH1 and CH2 may be bonded together to form a wideband channel or used them without bonding based on CSI. Hence when PU2 = 0, i.e. PU2 is absent, the system model is approximated as

\[ y_c = H_c x_c + w_c \]  

Where \( c \) varies from 2 to 3 and it defines the channel used for communication.

When \( c = 2 \) it represents CH2 is used for communication. This condition occurs when PU1 = 1. Whereas \( c = 3 \) represents that the CH1 and CH2 are bonded together to form a wideband channel (CHB12) and is used for communication. This condition occurs when both the primary users are absent.

Where \( y_c \) is the received signal vector over \( c^{th} \) channel and is of size (2 \( \times \) 1). Where \( H_c \) is the channel gain matrix of size (2 \( \times \) 2). The element \( H_{c,j} \) of the matrix \( H_c \) defines the channel gain between receive antenna 1 and transmit antenna 2. Where \( x_c \) is the transmitted OFDM symbol vector over \( c^{th} \) channel and is of size (2 \( \times \) 1).

Where \( w_c \) represents the noise vector of size (2 \( \times \) 1). Each of the elements of the noise vector represents white Gaussian noise with zero mean and a variance \( \sigma_n^2 \).

In the presence of PU2, i.e. PU2 = 1, the CH1 is used opportunistically, whereas CH2 is used in an underlay manner i.e. transmission over CH2 is allowed with a constraint on transmission power of SU1 and here it is 1 W to mitigate the interference to the PU2. However, the transmission power of the PU2 creates interference to the SU2 receiver contributing to the noise at the receiver and affecting the QoS.

Hence, the signal received at SU2 is given as

When PU1 = 0, the received signal is over CH1 and is

\[ y_1 = H_1 x_1 + w_1 \]  

When PU1 = 1, the received signal is over CH2 and is

\[ y_2 = H_2 x_2 + w_2 + w_{ps} \]  

Where \( w_{ps} \) is the noise vector present at the receive antennas of SU2, due to presence of PU2 and it is defined as

\[ w_{ps} = P_{p2} \left| h_{ps} \right|^2 \]  

Where \( P_{p2} \) is the transmission power of PU2 and \( h_{ps} \) is the gain of the channel between PU2 and SU2. The element \( w_{ps} \) of the vector \( w_{ps} \) reflects the noise present at the receive antenna 2 of SU2 due to the presence of PU2.

The objective of the proposed system is to maximize the throughput of the SU under the constraint of the transmission power of 2 W and the targeted BER 10\(^{-1}\). In the case of the underlay channel access mode, the transmission power is limited to 1 W, i.e. PU2 interference threshold limit.

The maximum achievable throughput of SU1 in the absence of PU2 is

\[ Thr_{max} = CBW \log_2 \left( 1 + \frac{P_{s1} \left| H_{1} \right|^2}{w_c} \right) \]  

Where \( CBW \) is the channel bandwidth (CB1 = 20 MHz or CB2 = 40 MHz), \( P_{s1} \) is the transmission power of SU1, \( H_{1} \) is the channel gain, and \( w_c \) is the additive white Gaussian noise (AWGN) power. In the case of the underlay channel access mode, the maximum achievable throughput of the system gets reduced and is given as

\[ Thr_{2max} = CBW \log_2 \left( 1 + \frac{P_{s2} \left| H_{2} \right|^2}{w_c + P_{p2} \left| h_{ps} \right|^2} \right) \]  

The channel bandwidth \( CBW \) in this case is \( CB1 = 20 \) MHz. The proposed scheme is aware of the primary user activities as well as channel status (CSI). The CSI is reflected by the average SNR estimate at the receiver (SNR_{avg,csi}). The SNR_{avg, csi} is evaluated from the \( c^{th} \) channel estimate \( H_{c,estim(K)} \) for \( N \) subcarriers. Where \( K \) reflects the carrier number and it varies from 1 to \( N \). The average power of the received signal over \( c^{th} \) channel is
Where \( H_{c-estm}(K) \) is the coefficient of the \( c^{th} \) channel and \( K^{th} \) subcarrier, \( N \) defines the total number of the data plus pilot subcarriers. In the proposed system, \( SU \) is operating in SDM (2 × 2) MIMO mode. Hence without channel-bonding

\[
N = 228
\]  
(9)

However, with channel-bonding \( N \) becomes

\[
N = 456
\]  
(10)

Hence the SNR at the receiver of the MIMO system is

\[
SNR_{\text{MIMO}} = \frac{S_{\text{avg-estm}}}{n_{\text{var-estm}}}
\]  
(11)

Where \( n_{\text{var-estm}} \) is the noise variance \( \sigma^2 \) at the receiver over \( c^{th} \) channel.

The average estimate of the SNR in dB is

\[
SNR_{\text{avg-estm}} = 10\log_{10} \left( SNR_{\text{MIMO}} \right)
\]  
(12)

The computed \( SNR_{\text{avg-estm}} \) is compared with the SNR thresholds that are obtained empirically to select the MCS and the channel bandwidth in the absence of PUs. The SNR thresholds can be computed from the relations between the BER and SNR in terms of the coding gain (\( CG \)) for different modulations and code rate (MCS).

The probability of the bit error for BPSK in (2 × 2) MIMO SDM mode is [29]

\[
BER_{\text{BPSK}} = \frac{1}{2} \left[ 1 - \sqrt{\frac{\bar{\gamma}_{\text{bit}}}{1 + \bar{\gamma}_{\text{bit}}}} \right]
\]  
(13)

(Since diversity order is \( D = N_r - N_o + 1 = 1 \))

Where \( \bar{\gamma}_{\text{bit}} \) is the average signal to noise ratio and for Rayleigh distributed channel it is

\[
\bar{\gamma}_{\text{bit}} = \frac{E_b}{N_0} E \left( \alpha^2 \right)
\]  
(14)

Where \( \alpha \) is Rayleigh distributed.
When channel-bonding is applied the average throughput of the system is

\[ Thr_{RB-avg} = (P_{CHB})(Thr^1_{CHB}) + (P_{d1})(Thr^2) \]  

(22)

Where \( P_{CHB} \) reflects the probability of channel-bonding. Where \( P_{d2} \) defines the true CH2 detection probability, i.e. probability of transmission over CH2.

Where \( Thr^1_{CHB} \) defines the maximum value of the average throughput while communicating over a bonded channel. Where \( Thr^2 \) defines the maximum value of the average throughput while communicating over CH2. In the case of communication over channels without bonding, the throughput of the system can be defined as

\[ Thr_{RB-avg} = (P_{d1})(Thr^1_{1}) + (P_{d2})(Thr^2) \]  

(23)

Where \( Thr^1_{1} \) is the maximum average throughput of the system while communicating over CH1. Where \( P_{d1} \) defines the probability of true detection of CH1, i.e. the probability of the transmission over CH1.

3. ALGORITHM (CR-RCHBC)

In this section, we discuss the proposed joint rate and channel-bonding adaptation algorithm for optimizing the throughput of the MIMO-OFDM based CR system. The proposed scheme is aware of the activities of the primary users as well as the channel condition and it defines the channel bandwidth, modulation, and code rate for each of the packet to be transmitted over the selected channel. The channel selector is located at the transmitter of the SU and selects the channel for transmission of the packet using the soft information about the activities of the PUs and the selected channel bandwidth. The proposed scheme allows the system to adapt the channel bandwidth, i.e. channel-bonding and MCS jointly in the absence of both primary users PU1 and PU2. The proposed algorithm also defines the configuration of the system based on the selected channel bandwidth. In the presence of any of the PU, the controller defines MCS with a fixed channel bandwidth (CB1 = 20 MHz). In the absence of the channel-bonding adaptation, both the channels CH1 and CH2 are accessed independently by using an appropriate channel access scheme. The channel usage strategies considered in the proposed scheme are described in Table 2. The problem for the proposed scheme can be formulated as

\[ \text{Max} \quad Thr_{RB}(R_j, CBW) \]

\[ \begin{cases} 
(C1): R_j \in \{R_8, R_9, \ldots, R_j\} \\
(C2): CBW \in \{CB1, CB2\} \\
(C3): BER \leq BER_{tar}
\end{cases} \]

Where \( Thr_{RB} \) is the throughput of the MIMO-OFDM based adaptive CR system operating in SDM mode. Where \( R_j \) is the set of the rates defining modulation and coding rate combination. Where the range of \( j \) is \( 8 \leq j \leq 16 \).

The average transmission power in case of underlay channel access scheme is 1 W and in remaining modes, it is assumed to be 2 W.

The average SNR estimate \( SNR_{avg,estm} \) is evaluated at the receiver and is used to define the channel state condition in the form of CSI. The proposed controller at the receiver defines the rate \( R_j \) and the channel bandwidth (CBW) by using the information about the activities of PUs and CSI. It is assumed that the control information is conveyed to the SU1 transmitter over a feedback channel. The SNR thresholds required to define the rate and channel bandwidth are empirically obtained by considering predefined MCS and channel bandwidth. The SNR thresholds can also be computed using mathematical relations between BER and SNR equations as defined in the mathematical model. The SNR threshold \( SNR_{th} \) is the minimum SNR required to optimize the throughput of the system under the constraint of targeted BER and for defined transmission power. Hence to optimize the throughput of the system

\[ \text{If} \quad BER \leq BER_{tar} \]

\[ \text{Then} \quad SNR_{th} = SNR_{min} \]

The proposed scheme also defines transmit power based on the channel access scheme. The pseudo code for the proposed algorithm is depicted below.
4. SIMULATION RESULTS

In this section, we exercise the performance evaluation of the MIMO-OFDM based adaptive CR system with joint rate and channel-bonding adaptation scheme. The performance is investigated in the perfect spectrum-sensing environment. The channel-bonding scheme has been exploited to the multi-user and multi-channel CR environment to enhance the throughput of the CR network. The performance of the proposed joint rate and channel-bonding adaptation scheme, which is aware of the PU activity and CSI, is compared with the system performance based on PU activity aware adaptive channel-bonding scheme. The throughput and BER are the metrics involved in the investigation of system performance. The effect of the proposed CR-RCHBAC on the performance of the system has been analyzed for different channel-bonding probabilities reflecting the importance of efficient channel detection and its utilization. The performance of the CR system with an adaptive joint rate and a channel-bonding scheme is compared with the CR system performance without channel-bonding in the presence of the PUs. The channels CH1 or CH2 or wideband channel CHB12 (CH1 + CH2) are accessed using different channel access schemes such as interweave, underlay, hybrid (interweave-underlay) based on the activities of the PUs. The system performance is validated by comparing the empirical results with the theoretical results that are obtained using SNR and BER relations for the rate-adaptive MIMO-OFDM system over the Rayleigh channel. The empirical analysis of the proposed system has been performed with MATLAB simulation. The simulation is based on the system design parameters described in Table 1. The performance analysis of the system considers the following cases.

4.1. Performance in the absence of the PU2 (PU2 = 0):

This case reflects the operation of the system in an adaptive channel-bonding mode. In this case, we assume that the primary user PU2 is absent and the activity of the PU1 is approximated by random ON-OFF model. Hence with PU2 = 0 and PU1 = 1, both the channels are idle and available for SUs and are used to form a wide band channel with the help of the adaptive channel-bonding along with MCS selection based on CSI. In the presence of the PU1, the channels are used independently and SUs communicate over CH2. The activity of the PU1 is reflected by defining the true detection probability of the CH1 i.e. channel-bonding probability ($P_d1 = P_{CH1}$). The system performance has been investigated with different channel-bonding probabilities that reflect the percentage usage of the wideband channel by SUs during the communication. The throughput and the BER curves in an adaptive channel-bonding mode are illustrated in Fig. 3 and Fig. 4 respectively. The corresponding numerical values of the average throughput and the channel access scheme involved in each of the cases are described in Table 3.

Table 3: Performance in the absence of PU2

<table>
<thead>
<tr>
<th>$P_{CHB}$ %</th>
<th>$P_d1$ %</th>
<th>Channel used (Mbps)</th>
<th>Channel access scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0</td>
<td>CHB12</td>
<td>111.13</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>CHB12 and CH2</td>
<td>73.59</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
<td>CH2</td>
<td>46.52</td>
</tr>
</tbody>
</table>

E.g., the throughput curve, PCHB-100 reflects the hundred percent availability of the CH1. With PU2 = 0, CH2 is also idle reflecting the entire communication with adaptive channel-bonding based on CSI. The average throughput of the system is 111.13 Mbps and is at its maximum value.

In the case of PCHB-40, the 40 percent transmission is with an adaptive channel-bonding based on the CSI, and the remaining 60 percent transmission is over CH2 in an independent way giving average throughput of 73.59 Mbps. The result with PCHB-0 reflects that PU1 is active and no CH1 is available for adaptive channel-bonding. Hence, SU1 communicates with SU2 over CH2 without channel-bonding resulting in reduced throughput with an average value of 46.52 Mbps. The analysis with an adaptive channel-bonding reflects that the CH1 is used opportunistically (interweave scheme) based on activities of PU1 allowing the formation of the wideband channel to enhance the throughput of the system for transmission of the chunk of data. It has been observed that in the lower range of the SNR i.e. below 10 dB the system performance without channel-bonding (CHB1 = 20 MHz) is better compared to that of the system with the bonded channel.
Fig. 3. Throughput performance with an adaptive channel-bonding (PU2 = 0)

Fig. 4. BER performance with an adaptive channel-bonding (PU2 = 0) (CB2 = 40 MHz). The simulation results have shown that as the probability of the channel-bonding increases, the throughput of the system increases in linear proportion. However, the BER of the system with adaptive channel-bonding is more compared to that of the BER of the system without channel-bonding.

Fig. 5. Throughput performance without channel-bonding (PU2 = 1)

Fig. 6. BER performance without channel-bonding (PU2 = 1)

4.2. Performance in the presence of PU2 (PU2 = 1):

In this case, the system is allowed to use the channels without bonding i.e. independently with fixed band width of 20 MHz. Because of the presence of the PU2, the channel CH2 is allowed to be used by the SUs in an underlay manner under the constraint on the transmission power (1 W). In this case, SUs are allowed to access CH1 opportunistically based on the activities of the PU1 reflected by the channel true detection probability $P_{d1}$. Thus, $P_{d1}$ reflects the CH1 usage probability, whereas $P_{d2}$ reflects CH2 usage probability. The throughput and BER curves reflecting the performance of the system without channel-bonding are illustrated in Fig. 5 and Fig. 6 respectively. The concerned numerical values of the average throughput with different channel detection probabilities and channel access schemes are described in Table 4.

Table 4: Performance in the presence of PU2

<table>
<thead>
<tr>
<th>$P_{d1}$</th>
<th>$P_{d2}$</th>
<th>Channel used (CH)</th>
<th>Average throughput (Mbps)</th>
<th>Channel access scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0</td>
<td>CH1</td>
<td>51.98</td>
<td>Interweave</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>CH1 and CH2</td>
<td>42.84</td>
<td>Hybrid</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
<td>CH2</td>
<td>37.65</td>
<td>Underlay</td>
</tr>
</tbody>
</table>
E.g., the curves Pd1-40 (throughput and BER) reflect the performance of the system using CH1 and CH2 without bonding. In this case, the CH1 usage probability is 40 percent, whereas the CH2 usage probability is 60 percent. The average throughput of the system is 42.84 Mbps. This is much less, than the throughput obtained with 40 percent usage of the bonded channel, which is 73.59 Mbps.

The curves Pd1-0 reflect the performance of the system with 100 percent communication over CH2 in the presence of the PU2, because of the unavailability of the CH1. This defines the underlay channel access scheme. The average throughput of the system, in this case, is 37.65 Mbps and is at its minimum value due to the constraint on transmission power and the interference from PU2 at the receiver of the SU2.

4.3. Performance comparison of the proposed CR-RCHBAC with CR-PUAWCHB:

In this case, we explore the comparison between the performance of the proposed system based on joint rate and channel-bonding adaptation scheme (CR-RCHBAC) and the performance of the system with an adaptive channel-bonding scheme that is based on the activities of PUs (CR-PUAWCHB) without CSI. The proposed scheme select rate and channel bandwidth based on the soft information about activities of the PUs and CSI. The throughput and BER performances are shown in Fig. 7 and Fig. 8 respectively. The corresponding numerical values are depicted in the Table 5. The maximum average throughput of the system in the case of CR-RCHBAC is 111.13 Mbps and in the case of CR-PUAWCHB, it is 102.86 Mbps. These results signify that the simultaneous selection of the rate and channel bandwidth using PUs activities and CSI outperforms the adaptive channel-bonding scheme based on only PUs activities. The improvement in the throughput of the proposed scheme comes at the cost of the increased BER. This can be realized from the average BER value of the proposed scheme, which is 0.037, whereas in the case of the CR-PUAWCHB it is 0.031. These are the average BER values over the operating range of the system (SNR ≥10dB).

Table 5: Performance comparison

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Average throughput (Mbps)</th>
<th>Average BER (10 ≤ SNR ≤ 60)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR-RCHBAC</td>
<td>111.13</td>
<td>0.037</td>
</tr>
<tr>
<td>CR-PUAWCHB</td>
<td>102.86</td>
<td>0.031</td>
</tr>
</tbody>
</table>

4.4. Validation:

The system performances of the proposed scheme in case of adaptive channel-bonding (PU2 = 0) and the case of without channel-bonding (PU2 = 1) are validated by comparing them with the theoretical performances obtained using BER and SNR relations for rate-adaptive MIMO-OFDM system operated in (2 × 2) SDM mode over Raleigh channel. The throughput and BER curves show resemblance with the theoretical curves shown in Fig. 3 to Fig. 6. The theoretical average throughput with the channel bandwidth of 40 MHz is 163.51 Mbps and with channel bandwidth of 20 MHz it is 81.75 Mbps. In all of the cases considered here, it could be realized that the BER is less than the targeted BER of the value 10⁻¹ over the entire operating range.

5. CONCLUSION

The novel joint rate and channel-bonding adaptation scheme for MIMO-OFDM based CR system have been introduced in this treatise. The proposed scheme has been exploited to the CR environment to enhance the throughput of the system and ensure the transmission of a chunk of data with minimum delay. The adaptive controller CR-RCHBAC ensures the simultaneous selection of the MCS and channel bandwidth by using the soft information about the activities of the PUs and CSI. The performance of the proposed scheme has been investigated with different channel-bonding probabilities reflecting the percentage of the bonded channel usage. The simulation results reflect the proportionate increase
in the throughput of the system with an increase in channel-bonding probability. The system performance investigation with different channel-bonding probabilities signifies that the performance is a function of the activity model of the PU. The system with low activity ON-OFF model, outperforms the system with high activity ON-OFF model of the PU.

The performance of the system has also been investigated for the case in which channels are used without bonding \((PU2 = 1)\) and compared with the performance of the system for the case comprising usage of channels with an adaptive bonding. Tremendous improvement in the throughput of the system has been noticed when it utilizes an adaptive channel-bonding scheme to form a wideband channel. However, it comes at the cost of BER.

The performance of the proposed CR-RCHBAC scheme is compared with the traditional adaptive channel-bonding scheme CR-PUAWCHB. In the traditional scheme, the channel bandwidth is adapted independently and is based on the activities of the PUs without giving consideration for CSI. It can be noticed from the simulation results that the scheme for selecting MCS and channel bandwidth simultaneously by sensing PUs activities and CSI (CR-RCHBAC) outperforms the CR-PUAWCHB. However, improvement in the throughput comes at the cost of the BER.

The system performances with and without adaptive channel-bonding have been validated by comparing them with the theoretical performances of the MIMO-OFDM system over the Rayleigh channel. The proposed scheme performance shows a close resemblance to the theoretical performance. Thus, an adaptive channel-bonding scheme can be exploited to the CR systems that are part of the wireless sensor networks, cellular networks to ensure the tremendous boost in the performance of the CR networks. Such systems can be exposed to applications such as home automation, industrial automation, power grid networks, hospitals, weather monitoring systems, etc. Proposed scheme could be more useful in collecting the bulk of data of COVID-19 patients at high rate from different regions by implementing CR based WSN, WRAN etc. in hospitals and cities. In the future, the proposed scheme can be applied and investigated for the CR networks comprising more number of PUs, SUs, and channels. The proposed scheme can also be applied for the systems based on the different wireless communication standards. The system with different PU activity models can be investigated with the proposed channel-bonding adaptation scheme. In this treatise, we have considered two channels of bandwidth 20 MHz to form a wide band channel of 40 MHz, and these bandwidths are adapted. However, the scheme can be generalized and tested for the adaptation of multiple channel bandwidths.

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AUTHOR PROFILES

Santosh Itraj: is pursuing a Ph.D. in Electronics Engineering at Shivaji University Kolhapur, Maharashtra, India. He received his master’s degree in Electronics Engineering from Shivaji University Kolhapur. Presently he is working as an Associate Professor in the Department of Electronics and Telecommunication, SCoEM, Satara affiliated to Shivaji University Kolhapur. Previously he worked as an Associate professor in Mumbai University affiliated SSPMCOE Kankavali. His research interest is in the area of Wireless communication, Cognitive radio technology, Signal processing, Embedded systems. Email- ssitrai@yahoo.com.

Dr. Uttam Bombale: received a Ph.D. in Electronics Engineering from the Dhirubhai Ambani Institute of Information & Communication Technology [DA-IICT], Gandhinagar, and Gujarat, India. He received his master’s degree in Electronics & Telecommunication in 1994 from COE Pune. Presently he is working as a Professor in the Department of Technology Shivaji University, Kolhapur. He worked as an Associate Professor in Mumbai University affiliated engineering colleges. His research interest is in the area of Microstrip antennas, Microwave technology, and Wireless communication. He published papers in International journals and International conferences. Email- uttam_bombale@rediffmail.com.