Volume 9, Issue 2
April 2020

ITEE Journal
Information Technology & Electrical Engineering

ISSN: - 2306-708X

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

**[1]Santosh Itraj and [2]Dr. Uttam Bombale**
[1]D.O.T. Shivaji University, Kolhapur

[2] D.O.T. Shivaji University, Kolhapur

E-mail: [1]ssitraj@yahoo.com , [2]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 propagation 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 aware 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.

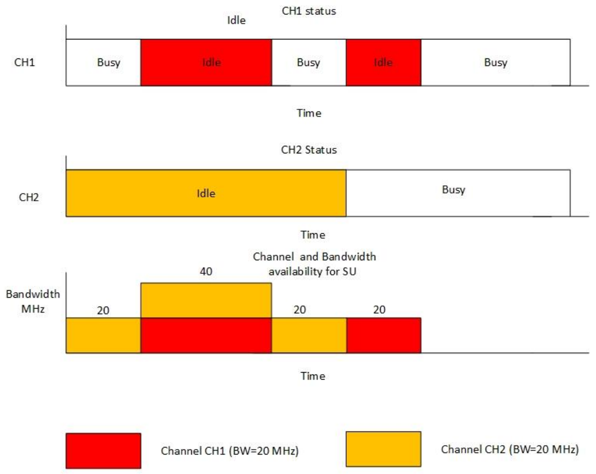


Fig. 1. Channel-bonding Concept

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 *SU1*) 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.

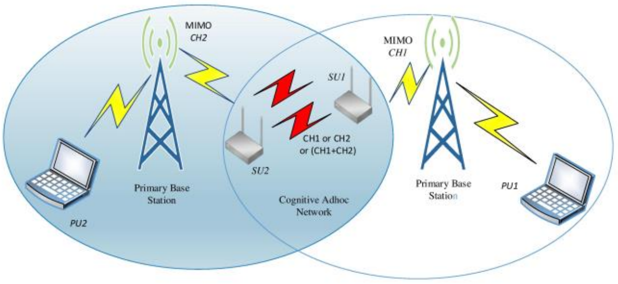


Fig. 2. System Environment

Table 1: System Design Parameters

| No. | System Parameter | Specification |
|---|---|---|
| 1 | WLAN Standard | HT–CBW20, HT-CBW40 modes |
| 2 | Guard interval | 800 ns |
| 3 | PSDU length | 1000 bytes |
| 4 | Maximum packet period | 1.3 ms |
| 5 | MIMO mode | (2 × 2) SDM |
| 6 | Targeted *BER* | $10^{-1}$ |
| 7 | Maximum average transmit power | 2W,<br>1W (For underlay mode) |

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 *SUs* to use *CH2*, i.e. whether *PU2* is absent or present. In the presence of the *PU2*, *SUs* are 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 *SUs* in an underlay manner. However, *SUs* have assigned higher priority to *CH1* and it has been accessed opportunistically. Thus, *CH1* is used by *SUs* only in the absence of the *PU1*. When *PU1* occupies the *CH1*, it is vacated by the *SUs* 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

$$N_{tr} = N_{re} = 2 \tag{1}$$

*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

$$y_c = H_c x_c + w_c \tag{2}$$

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 wide band 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 × 1).

Where $H_c$ is the channel gain matrix of size (2 × 2). The element $H_{c\text{-}12}$ 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 × 1).

Where $w_c$ represents the noise vector of size (2 × 1).

Each of the elements of the noise vector represents white Gaussian noise with zero mean and a variance $\sigma^2_{cn}$.

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

$$y_1 = H_1 x_1 + w_1 \tag{3}$$

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

$$y_2 = H_2 x_2 + w_2 + w_{ps} \tag{4}$$

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

$$w_{ps} = P_{p2} \left| h_{ps} \right|^2 \tag{5}$$

Where $P_{p2}$ is the transmission power of *PU2* and $h_{ps}$ is the gain of the channel between *PU2* and *SU2*. The element $w_{ps\text{-}2}$ 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

$$Thr_{\max} = CBW \log_2 \left( 1 + \frac{P_{s1} \left| H_c \right|^2}{w_c} \right) \tag{6}$$

Where *CBW* is the channel bandwidth (*CB1* = 20 MHz or *CB2* = 40 MHz), $P_{s1}$ is the transmission power of *SU1*, $H_c$ 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

$$Thr_{2\max} = CBW \log_2 \left( 1 + \frac{P_{s2} \left| H_2 \right|^2}{w_2 + P_{p2} \left| h_{ps2} \right|^2} \right) \tag{7}$$

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 ($SNR_{avg\text{-}estm}$). The $SNR_{avg\text{-}estm}$ is evaluated from the $c^{th}$ channel estimate $H_{c\text{-}estm}(K)$ 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

$$S_{cavg-estm} = \frac{1}{N}\sum_{K=1}^{N}\left|H_{c-estm}(K)\right|^{2} \qquad (8)$$

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

$$N = 228 \qquad (9)$$

However, with channel-bonding *N* becomes

$$N = 456 \qquad (10)$$

Hence the SNR at the receiver of the MIMO system is

$$SNR\_MIMO = \frac{S_{cavg-estm}}{n_{cvar-estm}} \qquad (11)$$

Where $n_{cvar-estm}$ is the noise variance $\sigma^2_{\ cn}$ at the receiver over $c^{th}$ channel.
The average estimate of the *SNR* in dB is

$$SNR_{avg-estm} = 10\log_{10}\left(SNR\_MIMO\right) \qquad (12)$$

The computed $SNR_{avg-estm}$ 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]

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

(Since diversity order is $D = N_{tr} - N_{re} + 1 = 1$)

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

$$\overline{\gamma}_{bit} = \frac{E_b}{N_0}E\left(\alpha^2\right) \qquad (14)$$

Where *α* is Rayleigh distributed.

For M-QAM the probability of bit error is

$$BER_{M-QAM} = \left(2\left(1-\frac{1}{\sqrt{M}}\right)\frac{1}{\log_2 M}\right)Q_m \qquad (15)$$

Where $Q_m$ is

$$Q_m = \left(\sum_{j=1}^{\sqrt{\frac{M}{2}}}\left(1-S_Q\right)\right) \qquad (16)$$

Where $S_Q$ is

$$S_Q = \sqrt{\frac{1.5(2j-1)^2\left(\overline{\gamma}_{bit}\right)\log_2 M}{M-1+1.5\left(2j-1\right)^2\left(\overline{\gamma}_{bit}\right)\log_2 M}} \qquad (17)$$

The above expression can be expressed in terms of *SNR* to get modified versions of the equations for *BER* expressed in [29] by replacing

$$\overline{\gamma}_{bit} = \left(\frac{B_s}{r_b}SNR\right)CG \qquad (18)$$

Where $r_b$ is the maximum bit transmission rate based on MCS, $B_s$ defines the signal bandwidth and is 250 KHz.
Where *CG* is the code gain defined as

$$CG = r_c d_{mini} \qquad (19)$$

Where $r_c$ is the coding rate and $d_{mini}$ is the minimum free distance based on code rate.
The throughput of the system in terms of *PER* is

$$Thr_{RB} = r_b\left(1-PER_{RB}\right) \qquad (20)$$

Where *PER* is defined as

$$PER_{RB} = \left(1-\left(1-BER\right)^{P_l}\right) \qquad (21)$$

Where $P_l$ is the length of the packet in bytes.

Table 2: Channel usage summary

| *PU1* | *PU2* | Channel used | Access scheme | Probability of Channel usage | Channel bandwidth MHz |
|---|---|---|---|---|---|
| 0 | 0 | *CHB12 or CH2* | Interweave | $P_{CHB}=P_{d1}$ | 40 or 20 |
| 0 | 1 | *CH1* | Interweave | $P_{d1}$=100% | 20 |
| 1 | 0 | *CH2* | Interweave | $P_{d2}$=100% | 20 |
| 1 | 1 | *CH2* | Underlay | $P_{d2}$=100% | 20 |

When channel-bonding is applied the average throughput of the system is

$$Thr_{RB-avg} = \left(P_{CHB}\right)\left(Thr_{CHB}\right) + \left(P_{d2}\right)\left(Thr_{2}\right) \tag{22}$$

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 $Thr_{CHB}$ 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

$$Thr_{RB-avg} = \left(P_{d1}\right)\left(Thr_{1}\right) + \left(P_{d2}\right)\left(Thr_{2}\right) \tag{23}$$

Where $Thr_1$ 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-RCHBAC)

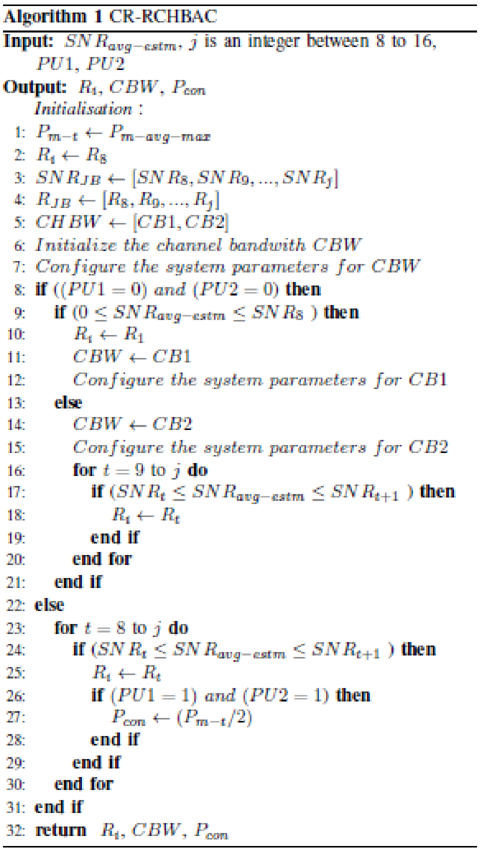
In this section, we discuss the proposed joint rate and channel-bonding adaptation algorithm for optimizing the throughput of the MIMO-OFDM based CR system. The proposed scheme is aware of the activities of the primary users as well as the channel condition and it defines the channel bandwidth, modulation, 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

$$\underset{R_J,CBW}{Max} \quad Thr_{RB}\left(R_J, CBW\right)$$
$$\begin{cases} C(1): R_J \in \left\{R_{8,}R_9 --- R_j\right\} \\ C(2): CBW \in \left\{CB1, CB2\right\} \\ C(3): \quad BER \le BER_{tar} \end{cases}$$

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 ($8 \le j \le 16$).
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

$$\begin{aligned} &If \quad\quad BER \le BER_{tar} \\ &Then \quad SNR_{th} = SNR_{\min} \end{aligned}$$

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



```
Algorithm 1 CR-RCHBAC
Input: $SNR_{avg-estm}$, $j$ is an integer between 8 to 16,
    $PU1$, $PU2$
Output: $R_t$, $CBW$, $P_{con}$
    Initialisation :
$P_{m-t} \leftarrow P_{m-avg-max}$
$R_t \leftarrow R_8$
$SNR_{JB} \leftarrow [SNR_8, SNR_9, ..., SNR_j]$
$R_{JB} \leftarrow [R_8, R_9, ..., R_j]$
$CHBW \leftarrow [CB1, CB2]$
$Initialize\ the\ channel\ bandwith\ CBW$
$Configure\ the\ system\ parameters\ for\ CBW$
if $((PU1 = 0)\ and\ (PU2 = 0))$ then
    if $(0 \leq SNR_{avg-estm} \leq SNR_8\ )$ then
        $R_t \leftarrow R_1$
        $CBW \leftarrow CB1$
        $Configure\ the\ system\ parameters\ for\ CB1$
    else
        $CBW \leftarrow CB2$
        $Configure\ the\ system\ parameters\ for\ CB2$
        for $t = 9$ to $j$ do
            if $(SNR_t \leq SNR_{avg-estm} \leq SNR_{t+1}\ )$ then
                $R_t \leftarrow R_t$
            end if
        end for
    end if
else
    for $t = 8$ to $j$ do
        if $(SNR_t \leq SNR_{avg-estm} \leq SNR_{t+1}\ )$ then
            $R_t \leftarrow R_t$
            if $(PU1 = 1)\ and\ (PU2 = 1)$ then
                $P_{con} \leftarrow (P_{m-t}/2)$
            end if
        end if
    end for
end if
return $R_t$, $CBW$, $P_{con}$
```

## 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* = 0, 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 ($P_{d1}$ = $P_{CHB}$). 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*

| $P_{CHB}$ % | $P_{d2}$ % | Channel used (*CH*) | Average throughput (Mbps) | Channel access scheme |
|---|---|---|---|---|
| 100 | 0 | *CHB12* | 111.13 | Interweave |
| 40 | 60 | *CHB12 and CH2* | 73.59 | Interweave |
| 0 | 100 | *CH2* | 46.52 | Interweave |

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 (*CB1* = 20 MHz) is better compare to that of the system with the bonded channel

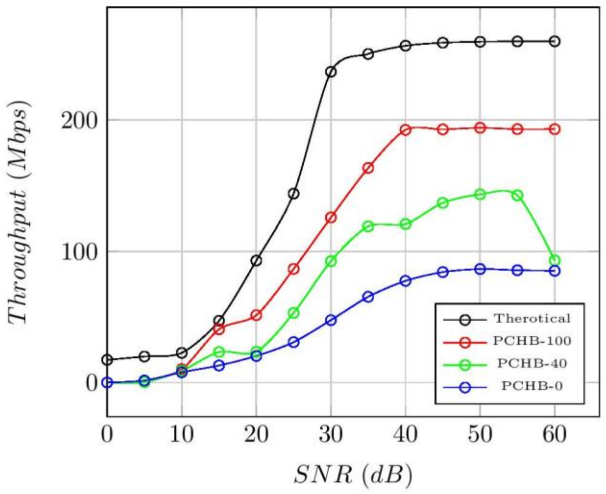


Fig. 3. Throughput performance with an adaptive channel-bonding (*PU2* = 0)

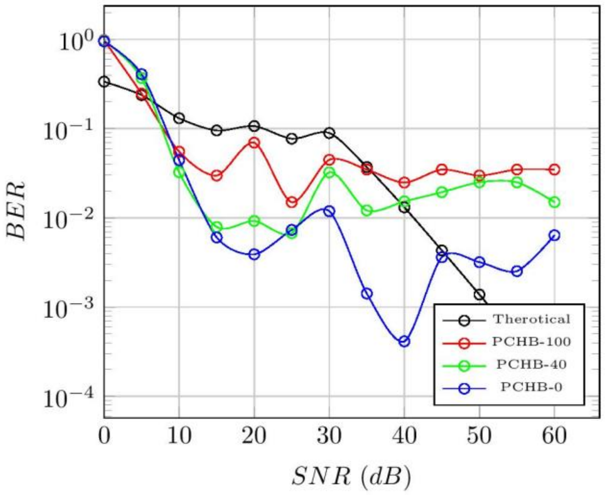


Fig. 4. BER performance with an adaptive channel-bonding (*PU2* = 0)

(*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.

## 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.

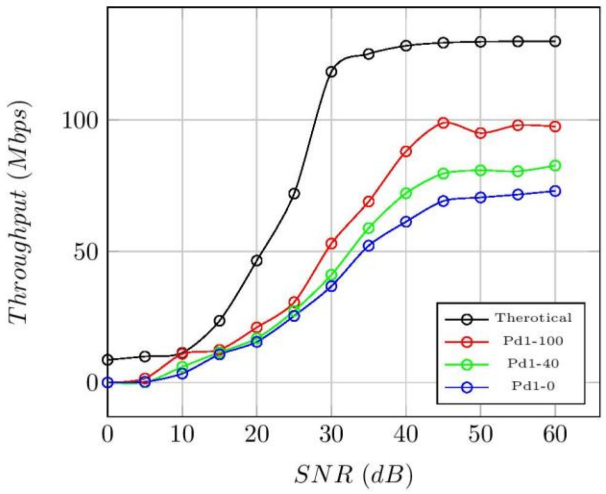


Fig. 5. Throughput performance without channel-bonding (*PU2* = 1)

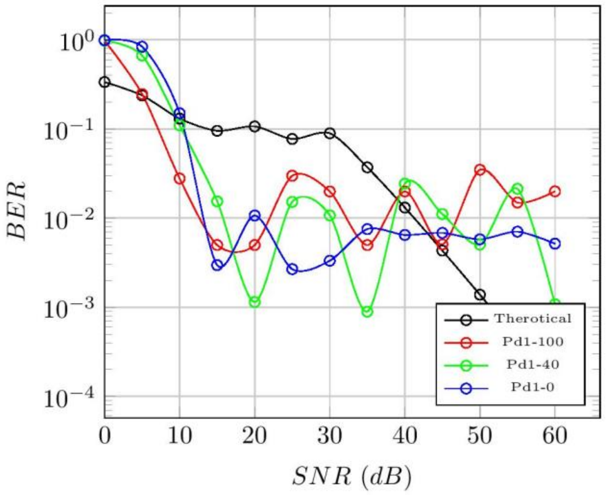


Fig. 6. BER performance without channel-bonding (PU2 = 1)

Table 4: Performance in the presence of *PU2*

| $P_{d1}$ % | $P_{d2}$ % | Channel used (*CH*) | Average throughput (Mbps) | Channel access scheme |
|---|---|---|---|---|
| 100 | 0 | *CH1* | 51.98 | Interweave |
| 40 | 60 | *CH1* and *CH2* | 42.84 | Hybrid |
| 0 | 100 | *CH2* | 37.65 | Underlay |

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

| Scheme | Average throughput (Mbps) | Average BER (10 ≤ SNR ≤60) |
|---|---|---|
| CR-RCHBAC | 111.13 | 0.037 |
| CR-PUAWCHB | 102.86 | 0.031 |

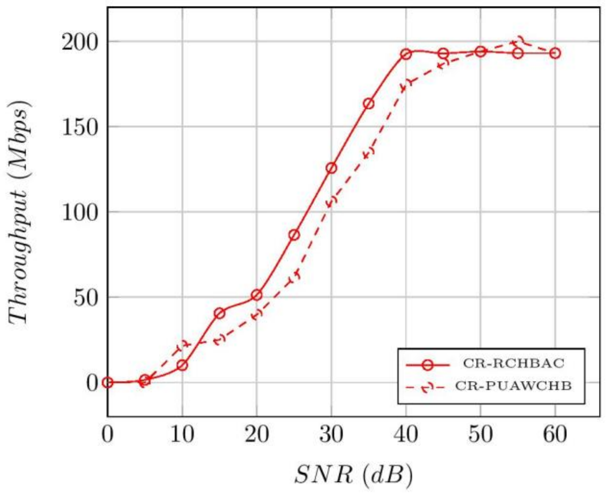


Fig. 7. Throughput performance comparison

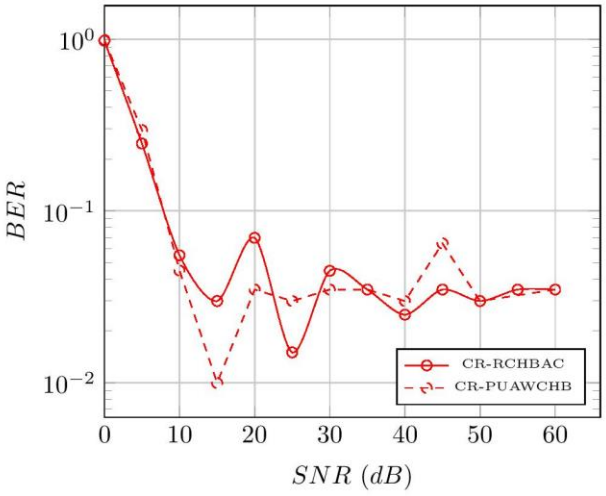


Fig. 8. BER performance comparison

### 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.

## REFERENCES

[1] M. Marcus J. Burtle, B. Franca, A. Lahjouji, and N.McNeil, “Federal communications commission spectrum policy task force,” Report of the unlicensed devices and experimental licenses working group, 2002.

[2] B. Wang and K. R. Liu, “Advances in cognitive radio networks: A survey,” IEEE Journal of selected topics in signal processing, vol. 5, no. 1, pp. 5–23, 2010.

[3] G. Scutari, D. P. Palomar, and S. Barbarossa, “Cognitive mimo radio,” IEEE Signal Processing Magazine, vol. 25, no. 6, pp. 46–59, 2008.

[4] B. Kumar, S. Kumar Dhurandher, and I. Woungang, “A survey of overlay and underlay paradigms in cognitive radio networks,” International Journal of Communication Systems, vol. 31, no. 2, p. e3443, 2018.

[5] A. Fakhrudeen and O. Y. Alani, “Comprehensive survey on quality of service provisioning approaches in cognitive radio networks: Part one,” International Journal of Wireless Information Networks, vol. 24, no. 4, pp. 356–388, 2017.

[6] Y. Zhao, S. Jin, and W. Yue, “An adjustable channel bonding strategy in centralized cognitive radio networks and its performance optimization,” Quality Technology & Quantitative Management, vol. 12, no. 3, pp. 293–312, 2015.

[7] M. H. Rehmani, S. Lohier, and A. Rachedi, “Channel bonding in cognitive radio wireless sensor networks,” in 2012 International Conference on Selected Topics in Mobile and Wireless Networking. IEEE, pp. 72–76, 2012.

[8] S. Hashim Raza Bukhari, S. Siraj, and M. Husain Rehmani, “Wireless sensor networks in smart cities: Applications of channel bonding to meet data communication requirements,” Transportation and Power Grid in Smart Cities: Communication Networks and Services, pp. 247–268, 2018.

[9] L. Deek, E. Garcia-Villegas, E. Belding, S.-J. Lee, and K. Almeroth, “Intelligent channel bonding in 802.11 n wlans,” IEEE Transactions on Mobile Computing, vol. 13, no. 6, pp. 1242–1255, 2013.

[10] S. Joshi, P. Pawełczak, D. Cabric, and J. Villasenor, “Performance of channel bonding for opportunistic spectrum access networks,” in 2012 IEEE Global Communications Conference (GLOBECOM). IEEE, pp. 1676–168, 2012.

[11] L. Deek, E. Garcia-Villegas, E. Belding, S.-J. Lee, and K. Almeroth, “The impact of channel bonding on 802.11 n network management,” in Proceedings of the Seventh Conference on emerging Networking Experiments and Technologies, pp. 1–12, 2011.

[12] L. Xu, K. Yamamoto, and S. Yoshida, “Performance comparison between channel-bonding and multi-channel csma,” in 2007 IEEE Wireless Communications and Networking Conference. IEEE, pp. 406–410, 2007.

[13] R. Chandra, R. Mahajan, T. Moscibroda, R. Raghavendra, and P. Bahl, “A case for adapting

channel width in wireless networks," ACM SIGCOMM computer communication review, vol. 38, no. 4, pp. 135–146, 2008.

[14] L. Deek, E. Garcia-Villegas, E. Belding, S.-J. Lee, and K. Almeroth, "Joint rate and channel width adaptation for 802.11 mimo wireless networks," in 2013 IEEE International Conference on Sensing, Communications and Networking (SECON). IEEE, pp. 167–175, 2013.

[15] M. Y. Arslan, K. Pelechrinis, I. Broustis, S. V. Krishnamurthy, S. Addepalli, and K. Papagiannaki, "Auto-configuration of 802.11 n wlans," in Proceedings of the 6th International COnference, pp. 1–12, 2010.

[16] M. Han, S. Khairy, L. X. Cai, and Y. Cheng, Performance analysis of opportunistic channel bonding in multi-channel wlans," in 2016 IEEE Global Communications Conference (GLOBECOM). IEEE, 2016, pp. 1–6.

[17] Y. Lu, H. He, J. Wang, and S. Li, "Opportunistic spectrum access with channel bonding," in 2009 Fourth International Conference on Communications and Networking in China. IEEE, pp. 1–5, 2009.

[18] S. Joshi, P. Pawelczak, D. Cabric, and J. Villasenor, "When channel bonding is beneficial for opportunistic spectrum access networks," IEEE Transactions on Wireless Communications, vol. 11, no. 11, pp. 3942–3956, 2012.

[19] S. H. R. Bukhari, S. Siraj, and M. H. Rehmani, "Pracb: A novel channel bonding algorithm for cognitive radio sensor networks," IEEE Access, vol. 4, pp. 6950–6963, 2016.

[20] Y. Konishi, Masuyama, S. Kasahara, and Y. Takahashi, "Performance analysis of dynamic spectrum handoff scheme with variable bandwidth demand of secondary users for cognitive radio networks," Wireless Networks, vol. 19, no. 5, pp. 607–617, 2013.

[21] J. Gao, X. Li, W. Wang, and Y. Bai, "Non-contiguous channel bonding for tv white space usage with nc-ofdm transmission," Wireless Personal Communications, vol. 86, no. 2, pp. 385–401, 2016.

[22] R. A. Rahim, R. Nordin, and M. Ismail, "Investigation of channel bonding based on tv white space spectrum occupancy for urban areas in malaysia," in 2014 2nd International Conference on Information and Communication Technology (ICoICT). IEEE, pp. 100–105, 2014

[23] M. E. Bayrakdar and A. Calhan, "Improving spectrum handoff utilization for prioritized cognitive radio users by exploiting channel bonding with starvation mitigation," AEU-International Journal of Electronics and Communications, vol. 71, pp. 181–191, 2017.

[24] H. Katayama, H. Masuyama, S. Kasahara, and Y. Takahashi, "Effect of spectrum sensing overhead on performance for cognitive radio networks with channel bonding," 2014.

[25] Y. Zhao, M. Peng, and J. Liu, "A hybrid spectrum access strategy with channel bonding and classified secondary user mechanism in multichannel cognitive radio networks," Sensors, vol. 19, no. 20, p. 4398, 2019.

[26] L. Jiao, V. Pla, and F. Y. Li, "Analysis on channel bonding/aggregation for multi-channel cognitive radio networks," in 2010 European Wireless Conference (EW). IEEE, pp. 468–474, 2010.

[27] S. Jin, X. Yao, and Z. Ma, "A novel spectrum allocation strategy with channel bonding and channel reservation." Ksii Transactions on Internet & Information Systems, vol. 9, no. 10, 2015.

[28] I. . W. Group et al., "Part 11: wireless lan medium access control (mac) and physical layer (phy) specifications, amendment 5: enhancements for higher throughput," IEEE Std, vol. 802, 2009.

[29] M. K. Simon and M.-S. Alouini, Digital communication over fading channels. John Wiley & Sons, vol. 95, 2005.

## 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- ssitraj@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