IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received August 26, 2016, accepted October 6, 2016, date of publication October 24, 2016, date of current version November 8, 2016.

Digital Object Identifier 10.1109/ACCESS.2016.2618418

PRACB: A Novel Channel Bonding Algorithm for Cognitive Radio Sensor Networks

SYED HASHIM RAZA BUKHARI[1,2], SAJID SIRAJ[1,3], and MUBASHIR HUSAIN REHMANI[1]
[1]COMSATS Institute of Information Technology, Wah Cantonment 47040, Pakistan
[2]COMSATS Institute of Information Technology, Attock 43600 , Pakistan
[3]Leeds University Business School, LS6 1AN Leeds, U.K.

Corresponding author: S. H. R. Bukhari (hashimbukhari01@gmail.com)

ABSTRACT Wireless sensor networks (WSNs) can utilize the unlicensed industrial, scientific, and medical (ISM) band to communicate the sensed data. The ISM band has been already saturated due to the overlaid deployment of WSNs. To solve this problem, WSNs have been powered up by cognitive radio (CR) capability. By using CR capability, WSNs can utilize the spectrum holes opportunistically. The sensor nodes, which need large bandwidth to transmit their sensed data from source to destination require some scheme, which should be able to provide them a wide band channel whenever required. Channel bonding (CB) is a technique through which multiple contiguous channels can be combined to form a single wide band channel. By using CB technique, CR-based WSN nodes attempt to find and combine contiguous channels to avail larger bandwidth. In this paper, we show that by increasing the number of channels, the probability of finding contiguous channels decreases. Moreover, we then propose a primary-radio (PR) user-activity-aware CB algorithm and compare it with three state-of-the-art schemes: SWA, KNOWS, and AGILE. It has been demonstrated through extensive NS-2 simulations that intelligent CB decisions can reduce harmful interference to PR nodes. We find that CB in CR sensor networks attempts to provide greater bandwidth and utilizes the spectrum effectively.

INDEX TERMS Channel bonding, cognitive radio, dynamic spectrum access, wireless sensor networks.

I. INTRODUCTION

WSNs have been deployed everywhere around us and integrated with our daily life operations. WSNs have been implemented in automation of processes ranging from house hold applications to industry [1], [2]. Some common applications of WSNs include home automation [3], services in urban areas [4], mobile target tracking [5], medical applications [6], battle field surveillance, forest fire detection, and industrial automation [7]. All of these applications utilize ISM band for communication as it is freely available in all parts of world. The ISM band is over crowded due to vast deployment of these networks such as, indoor sensing applications, multimedia applications and multiclass heterogeneous sensing applications [8]. The overlaid deployment of WSNs over same geographical area adds to the spectrum scarcity [9]. It increases the chances to introduce collisions while trying to acquire same frequency band at the same time or to add delay in accessing a specific band.

A. COGNITIVE RADIOS IN WSN

By adding cognitive radio capabilities to WSNs, one can take advantage of dynamic spectrum allocation based on cognitive cycle [8], [10]. The sensor nodes are hence called Cognitive Radio (CR) nodes and network based on CR nodes is called Secondary network or CRSN. CR nodes (unlicensed users) can access both licensed and unlicensed band whenever they are available and the nodes have capability to utilize them. The licensed users have priority to access the spectrum and hence called Primary Radio (PR) nodes. The cognitive cycle is responsible for sensing spectrum holes, providing access to CR nodes and release them whenever PR node becomes active [11]. In this way, the problem of overlaid deployment of multiple WSNs have been solved and amount of collisions can be significantly reduced. Cognitive radio technology in WSNs has also made it independent of different spectrum regulations in different parts of world as CR nodes can access and utilize any spectrum band by keeping the threshold of interference lower than specified level [12].

B. CHANNEL BONDING

Wireless Multimedia Sensor Networks (WMSNs) have become famous to provide multimedia services to various type of applications such as environmental monitoring, location tracking and health care etc. These applications require high bandwidth as sensor nodes sense and transmit multimedia data [29]. Also this data needs to be sent in real-time so high throughput is highly desirable. Channel Bonding (CB) has been a promising approach to satisfy the need of bandwidth hungry WMSN nodes [30]. Using this technique, multiple free narrow-band contiguous channels can be combined to make a large wide-band channel. CB technique has been used in cellular networks to increase the spectral resources [17]. The devices are now equipped with multiple network interfaces which sense the spectrum holes in parallel for multiple networks and utilize them whenever found [31].

The application of CB technique in CRSNs opens a new research paradigm. The sensor nodes in CRSN are wireless in nature so energy consumption must be taken into consideration while implementing channel bonding [32]. CB can be helpful in providing large bandwidth to CR users and using low transmission power, the energy of CR nodes can be conserved [20]. The use of low transmission power is also helpful in keeping the interference level low as coverage area can be reduced and same frequency can be utilized again after a considerable distance called as frequency re-use [33]. This characteristic of CB in CRSNs is of much use that now a dense deployment of sensor nodes in small geographical area has become possible. Also, multiple overlaid sensor networks can continue transmitting their sensed data without creating harmful interference to their neighbor channels and on the same time multimedia sensors can utilize high bandwidth whenever required [8]. While getting advantages of CB in CRSNs, it is to take care that CR nodes should not interrupt the services guaranteed to PR nodes. For this purpose, CR nodes may be required to break the bond and stop their transmissions to leave the channel empty for PR nodes [27].

C. CONTRIBUTION OF THIS ARTICLE

Our brief contributions in this article are as follows:

- We first characterize the behavior of channel bonding in presence of PR activities.
- We show that increasing the number of channels, the probability of finding contiguous channels decreases.
- We propose a primary radio user activity aware channel bonding (PRACB) algorithm and compare it with three state-of-the-art schemes: SWA, KNOWS, and AGILE.
- From extensive NS-2 simulations, we have showed that naive channel bonding can cause harmful interference to PR nodes.
- To the best of our best knowledge, there does not exists any protocol which supports CB in CRSNs. Hence, this paper proposes algorithms for CB strategy in CRSNs.
- We have performed detailed analysis of our proposed scheme and propose future goals for high bandwidth applications in CRSNs.

D. ARTICLE STRUCTURE

The rest of our paper is organized as, Section 2 is discussing the related work. In section 3, we discuss the proposed channel bonding algorithm. Section 4 performs the detailed analysis of our proposed algorithm and the topic concludes in section 5 along with future recommendations.

II. RELATED WORK

In this section, we will provide the CB schemes which have been implemented in various types of networks, their discussion and analysis.

A wide implementation of CB schemes has been mentioned in [32], where as a brief discussion of these implementations has been summarized as Table. 1.

A. CHANNEL BONDING IN CELLULAR NETWORKS

Channel bonding in Cellular networks has been implemented which has opened a new era of next generation cellular networks. These networks can adopt their operating frequency in licensed as well as unlicensed bands [13], [15]–[17]. By operating into these bands, cellular networks can dynamically access the spectrum holes and can behave as CR node. Cellular nodes are normally independent of battery issues so they can continue consuming large bandwidth at the cost of high power consumption. New fascinating applications of next generation cellular networks have become possible due to CB techniques which are capable of providing high bandwidth. The cellular phones are re-chargeable so power consumption is not a major issue while increasing bandwidth but still there is a need of developing such protocol which can make the CB scheme battery friendly [20]. A channel bonding model has been presented in [14] where a node can sense multiple channels in a spectrum to utilize them as required. These nodes also share the information related to these opportunistic channels with their base stations so that the base station can also adjust their operating frequency in case of CB. However by using CB scheme, the orthogonality between the channels can be lost which can be exploited by attackers [34]. These attackers can create harmful interference which will disturb the PR traffic and the QoS of channel. Hence secure CB schemes are needed to be developed to address these vulnerabilities. IEEE P802.22 draft standard has allowed CB to be utilized for wireless RANs [35]. Similarly, CB technique has also been used by WLANs [36], WSNs [37] and CRNs [38] to improve their bandwidth conditions.

B. CHANNEL BONDING IN WSNs

WSNs can also get benefit from CB scheme by combining contiguous free channels. By using CB scheme, the channel width can be increased but at the cost of reduced transmission range. As WSNs are battery powered nodes, so power consumption is an important metric which determines the network life time. When channel width is increased using CB scheme, the transmission range can be maintained unchanged but at the cost of more power consumption. This is the reason

TABLE 1. Application of CB schemes in literature. These channel bonding schemes have been applied to a variety of networks such as cellular networks, wireless sensor networks and cognitive radio networks.

Reference	Year	Network	Description
[13]	2006	Cellular	A scheme for cellular channel bonding for high data transmission
[14]	2009		A concept of OSA with CB in cellular networks
[15]	2013		The concept of transmission enhancement features for LTE-Advanced in cellular networks
[16]	2014		A survey of resource management schemes for LTE-Advanced cellular networks
[17]	2014		A review of CA/CB schemes in next generation cellular networks
[18]	2008	WSN	A method of improving throughput through varying channel width
[19]	2008		The study of channel assignment problem for dynamic width channels
[20]	2008		Adapting channel width for high data rates
[21]	2009		An efficient joint channel assignment technique for enhancing network capacity
[22]	2011		The impact of CB technique on 802.11n network management
[23]	2007	CRN	The performance comparison of CB and multi-channel CSMA
[24]	2008		The discussion of narrow band friendly wide bands in CRNs
[25]	2009		Directions for high speed cognitive radio networks
[26]	2012		The issues of dynamic spectrum access in CRNs
[27]	2012		The discussion of Opportunistic spectrum access in 802.22 networks
[28]	2013		The issues of guard band with CB in CRNs

which suggests the compromise of transmission range and to conserve power [22]. Increasing transmission range also increases the probability of interference with other users. This interference can be avoided using variable width frequency allocations [18]. As there is no concept of PR traffic in WSNs so all the nodes have same priority and share the same set of channels. Using variable width frequency allocations, CB can be applied when channels are free and WSN node get a burst to transmit. Dynamic channel assignment for WLAN depending upon the traffic mass has been presented in [19] and the same can be applied to WSNs by considering the effect on power consumption. When low throughput is required, a narrower channel can be used while in case of high throughput requirement, CB can be used for dynamic channel assignment [20]. Although CB can mitigate the bandwidth hunger of WSN nodes but the demand cannot be fully served due to the absence of cognitive radio capabilities. All the nodes in a network sharing same set of channels can utilize CB only with consultation of channel assignment protocol such as CSMA. This situation leads to frequency wastage due to non-utilization of spectrum holes present in other channels.

C. CHANNEL BONDING IN CR BASED NETWORKS

To cope the problem with static resource allocation in overcrowded radio spectrum, CR based networks have been considered as a reasonable solution [25]. By using the process of dynamic spectrum allocation (DSA), CRNs access the spectrum holes present in licensed as well as in unlicensed bands [26]. Once these holes have been identified, a bond can be established to meet the high bandwidth requirement. As, CRNs consider PR activity, so it is worth noting that suitability of a channel for channel bonding depends upon the type of PR activity over that channel [27]. Those channels having low PR activity are suitable for CB as there are few chances for harmful interference to happen. To reduce the chances of adjacent channels interference, the concept of guard band is used. The size of guard bands can be optimized using the scheme proposed in [28] using which the spectrum allocation protocol can dynamically adjust the size of guard band depending upon the traffic state on channel. CB is no doubt an effective solution to increase bandwidth and minimize delay [23] but still its true advantage cannot be gained due to limitations of CRNs. The static nature of CR based networks refrain the nodes to achieve the maximum benefits of CB using DSA. Some of the important challenges for CR based networks are to minimize interference, avoid contention and to maximize the use of limited bandwidth assigned to the given network [24], [39].

D. CHANNEL BONDING IN CRSNs

CRSNs are WSNs having cognitive capabilities can cope easily with mobility issue as these sensor nodes can be static as well as mobile. The involvement of wireless multimedia sensor nodes (WMS) is a new addition in WSN family. When these WMS have some data to transmit, they require high bandwidth for which CB is the suitable candidate. While applying CB in CRSNs, power consumption and PR traffic both are needed to be considered. As per our best knowledge, there does not exists any protocol which can provide CB capability in CRSNs. In this paper we propose an algorithm PRACB which is capable of providing CB scheme while considering PR traffic. Extensive simulations have been performed to show that our proposed protocol successfully increases bandwidth and provide a high speed link to CR nodes.

E. SUMMARY

To summarize the discussion, there is no scheme available in literature to provide CB for CRSNs. We are the first one to propose an intelligent CB scheme for CRSN which attempts to provide maximum bandwidth while avoiding harmful interference to PR nodes.

III. PRIMARY RADIO USER ACTIVITY AWARE CHANNEL BONDING (PRACB) ALGORITHM FOR CRSNs

In this section, we will discuss the working of our proposed primary user activity aware channel bonding algorithm.

TABLE 2. A summary of primary radio activity parameters.

PR Activity	λ_X	λ_Y	ON	OFF
Long Term Activity	$\lambda_X \leq 1$	$\lambda_Y \leq 1$	Long ON	Long OFF
High Activity	$\lambda_X \leq 1$	$\lambda_Y > 1$	Long ON	Short OFF
Low Activity	$\lambda_X > 1$	$\lambda_Y \leq 1$	Short ON	Long OFF
Intermittent Activity	$\lambda_X > 1$	$\lambda_Y > 1$	Short ON	Short OFF

A. SYSTEM MODEL AND ASSUMPTIONS

In this section, PR activity aware CB algorithm for CRSNs has been discussed. PR activity gives the information about presence or absence of PR users over the channel. We modeled the PR activity as continuous-time, alternating ON/OFF Markov Renewal Process (MRP) [40], [41]. This PR activity model has been widely used in the literature [40]–[45]. The ON/OFF PR activity model approximates the spectrum utilization pattern of voice networks [46] and also very famous for public safety bands [45], [47]. Table 2 shows the behavior of PR activities on wireless channel where the ON state represents that channel is currently busy and occupied by PR node. The OFF state represents that channel is idle and unoccupied by any PR node. The time duration for which the channel i is in ON and OFF states are denoted as T_{ON}^i and T_{OFF}^i respectively. The duration which a channel takes to complete one consecutive ON and OFF period is called renewal period. Let this renewal period for a channel i at time t is denoted by $Z_i(t) = T_{ON}^i + T_{OFF}^i = 1$ [41], [48], [49]. Both ON and OFF periods are assumed to be independent and identically distributed (i.i.d). Since each PR user arrival is independent so according to [49], each PR user arrival follows the Poisson arrival process and the length of ON and OFF periods are exponentially distributed with p.d.f. $f_X(t) = \lambda_X \times e^{-\lambda_X t}$ for ON state and $f_Y(t) = \lambda_Y \times e^{-\lambda_Y t}$ for OFF state. The time duration for which a channel i is being utilized by PR user is called utilization factor of i^{th} channel and can be written as:

$$u^i = \frac{E[T_{ON}^i]}{E[T_{ON}^i] + E[T_{OFF}^i]} = \frac{\lambda_Y}{\lambda_X + \lambda_Y} \tag{1}$$

where $E[T_{ON}^i] = \frac{1}{\lambda_X}$ and $E[T_{OFF}^i] = \frac{1}{\lambda_Y}$, λ_X and λ_Y are the rate parameters for exponential distribution. $E[T_{ON}^i]$ and $E[T_{OFF}^i]$ is the mean of exponential distribution [48]. In this way any kind of PR activity can be added by describing the pattern as discussed in [50]. We have used four types of PR activities i.e. Low, High, Long and Intermittent. The wireless parameters for these four types of PR activities has been shown as appendix in Tables. 3, 4, 5 and 6.

The CRSN nodes perform spectrum sensing through detecting energy threshold on the channel. Energy threshold is the most common way of sensing due to its low complexity, computational overhead and power requirements [51]. Let F is the total number of channels which can be sensed and $F = f_i$ where $i = 1, 2, ..., m$. Now $f_i = k(i) + n(i)$ where $k(i)$ is the signal to be detected and $n(i)$ is the additive white gaussian noise (AWGN) over the channel. Then the set of occupied channels F_o can be formulated as:

$$F_o = f_i : \phi(f_i) \geq \theta \tag{2}$$

Where θ is the threshold to take decision of a sensing function and $\phi(f_i)$ that declares channel to be in occupied state. Similarly the set of vacant channels F_v can also be formulated as:

$$F_v = f_i : \phi(f_i) \leq \theta \tag{3}$$

The two metrics which measure the efficiency of spectrum sensing are detection probability (P_d) and false alarm probability (P_f). S_a^i denotes the state of i^{th} channel that it is busy (PR node is active) with a probability $P_a^i = \lambda_Y/\lambda_X + \lambda_Y$ and S_b^i the state that the i^{th} channel is vacant (PR node is not active) with a probability $P_b^i = \lambda_X/\lambda_X + \lambda_Y$ such that $P_a^i + P_b^i = 1$. A high detection probability shows less chances of causing interference to PR nodes where as low false alarm probability indicates that a node does not skips the vacant slots mistakenly and utilizes the channel efficiently. According to [52], the detection and false alarm probability for i^{th} channel can be formulated as:

$$P_d^i = P_r\{\phi(f_i) \geq \theta | S_a^i\} = \frac{1}{2} erfc(\frac{1}{\sqrt{2}} \frac{\theta - 2n_i(\gamma_i + 1)}{\sqrt{4n_i(2\gamma_i + 1)}}) \tag{4}$$

$$P_f^i = P_r\{\phi(f_i) \geq \theta | S_b^i\} = \frac{1}{2} erfc(\frac{1}{\sqrt{2}} \frac{\theta - 2n_i}{\sqrt{4n_i}}) \tag{5}$$

The $erfc(.)$ is the error function and γ_i and n_i represent the signal to noise ratio (SNR) of the signal and bandwidth product for the i^{th} channel.

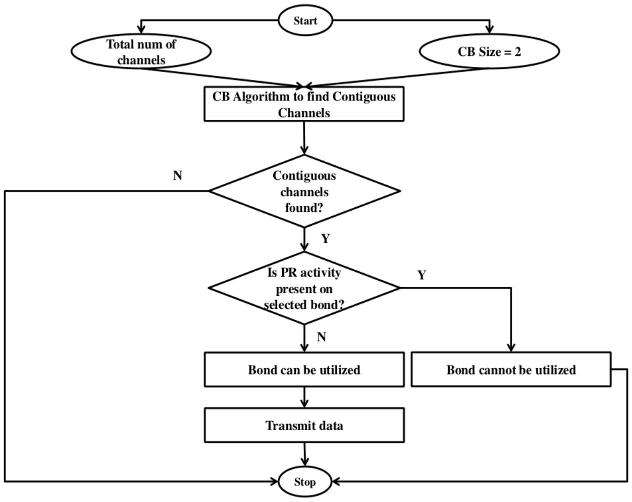
In spectrum sensing procedure through above mentioned equations, there is a possibility of causing interference to PR nodes due to imperfection in realistic scenarios. While "T" is the total transmission duration, the interference can be estimated as the ON duration of PR node mistakenly considered as idle at the i^{th} channel and can be formulated as follows [53]:

$$INTR_i = (1 - P_d^i)P_a^i + P_b^i(1 - P_f^i) + e^{-\lambda T}(P_f^i - P_d^i) \tag{6}$$

where λ_X^i and λ_Y^i are the birth and the death rate respectively and $\lambda = max(\lambda_X^i, \lambda_Y^i)$. We assume that CRSN nodes in our network use efficient spectrum sensing which minimizes the interference with PR nodes. The interference with PR nodes must be below the threshold i.e., $INTR_i \leq INTR_{max}^i$ where $INTR_{max}^i$ provides the maximum allowable interference on i^{th} channel.

After sensing the spectrum and minimizing the sensing interference, the CR nodes take decision to switch to suitable

Algorithm 1 PR User Activity Aware CB Algorithm for CRSNs (PRACB) for 2 Contiguous Channels



vacant channel. Considering the cases that channel sensing was able to identify the spectrum holes and no false alarms were generated, the channel switching probability *SP* can be formulated as [54]:

$$SP^i = P_a^i(1 - P_d^i) + P_b^i(1 - P_f^i) \tag{7}$$

Now, if ideal scenario is considered, the spectrum sensing will generate P_f^i as 0% and P_d^i as 100% then SP^i will be equal to P_b^i.

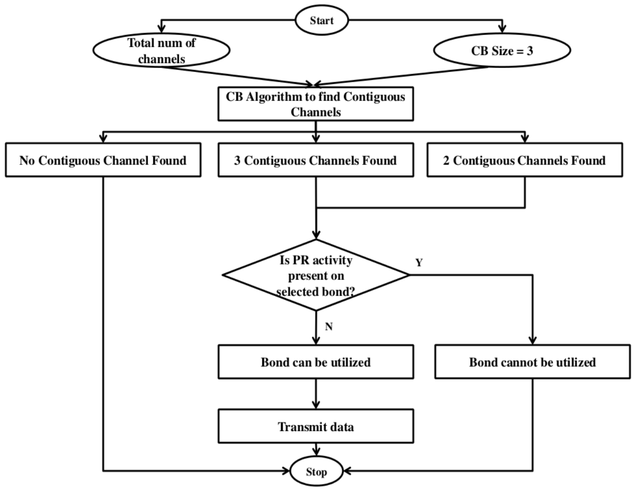
All these equations (cf. Eq. 1 to Eq. 7) are the building blocks for the smooth operation of our proposed channel bonding algorithms.

B. WORKING OF PR ACTIVITY AWARE CHANNEL BONDING ALGORITHM

Now we describe the working of our proposed PRACB algorithm. PRACB algorithm at CR node will first make a list of available channels. As a second step, it will prepare a list of available contiguous channels which can fulfill the current bandwidth requirement of CR node. Then the algorithm will perform spectrum sensing. The spectrum sensing will detect the presence of PR activity on channels.

Lets assume there are two CRSN nodes A and B deployed in communication range of each other. Node A has some multimedia data to be sent to node B. The available bandwidth of individual frequency channel is not sufficient to carry the data so node A will perform channel bonding. For smaller bond size, nodes can select bond size as 2 (as shown in algorithm 1). For larger bond size, node A sets the bond size as 3 (as shown in algorithm 2) and total number of available channels are 15. The channel bonding algorithm works on network layer and it finds the pairs of 3 contiguous channels randomly generated out of total available channels. This pair will be bonded and CR node will utilize this bond for communication. Along with this, algorithm also tries to find the pairs of 2 contiguous channels which is a sub-optimal case. All the information about availability of contiguous channels is then passed to MAC layer. MAC layer performs channel sensing and checks the state of PR activity on bonded channels. Now there are five possibilities at this stage, either there can be any of four PR activities present over the bond or channel can be idle. If there is no PR activity found on selected bond, the CR node will utilize the bond and transmits data otherwise the bond will be broken. The information of selected bonded channels is then be sent to the node B through control channel. The node B tunes its receiver to selected bandwidth and receives data correctly.

Algorithm 2 PR User Activity Aware CB Algorithm for CRSNs (PRACB) for 3 Contiguous Channels



IV. PERFORMANCE EVALUATION

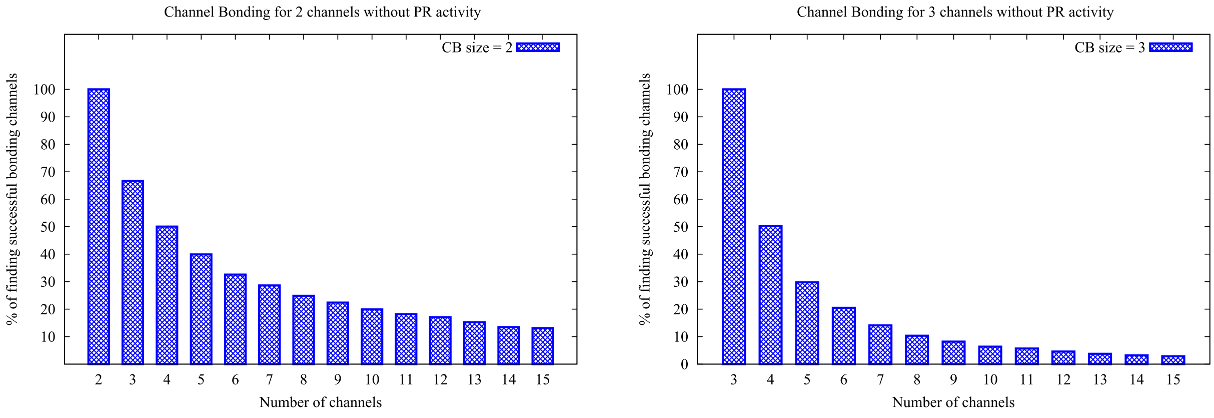
In this section, we will discuss the necessary changes in NS-2 to simulate our PRACB and then will evaluate the performance of PRACB with the help of simulation results.

A. MODIFICATION IN NS-2

We have chosen CRCN patch [55] in NS-2 to simulate our CRSN scenario. To simulate PRACB in NS-2, there are certain modifications required. CRCN patch in NS-2 does not consider PR activity hence it is required that first PR activity should be introduced so that CR nodes should be able to utilize only those channels which are free from PR nodes. Moreover, CRCN patch does not provide fully functional multiple channels support to CR nodes. Thus, after introducing PR activity, we added multiple channels support so that a CR node should be capable of realizing advantages of DSA and utilizing multiple channels for the purpose of channel bonding.

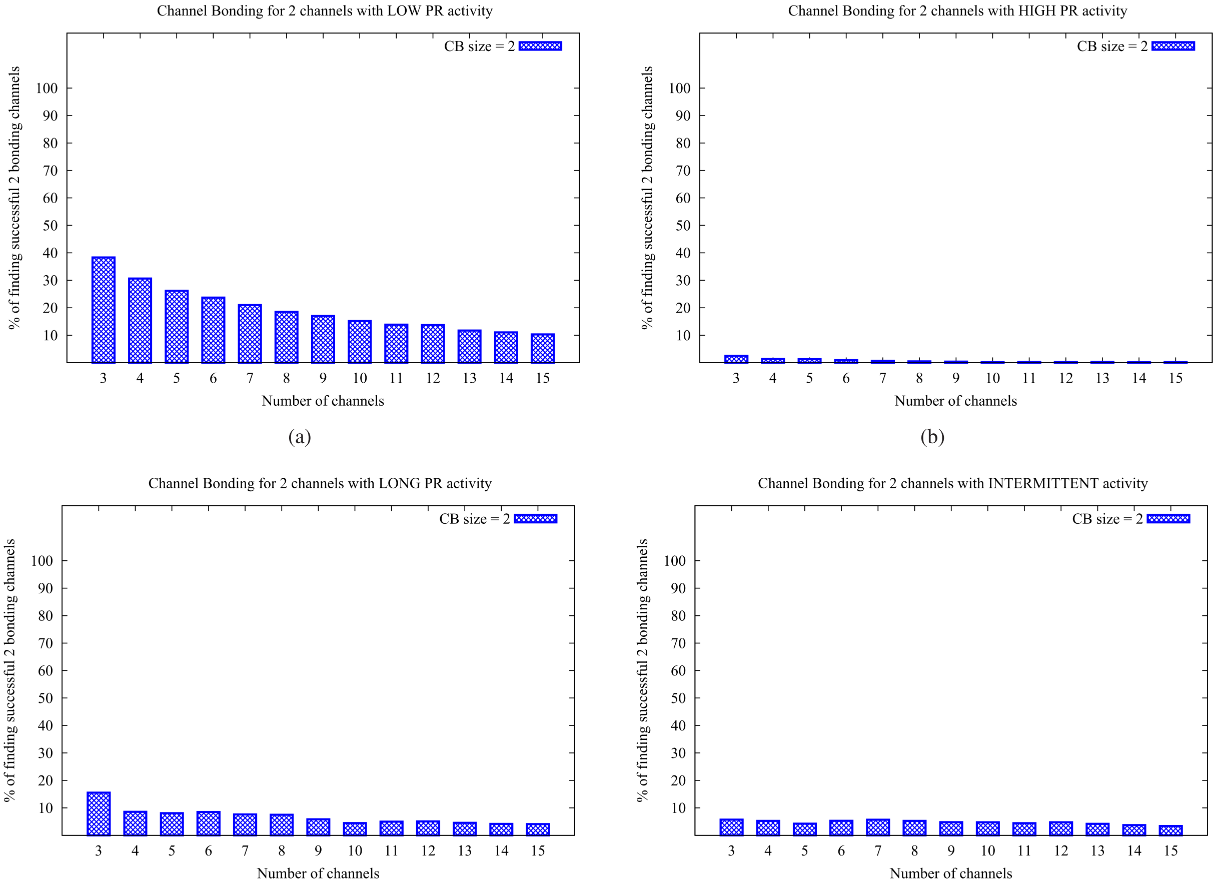
B. SIMULATION RESULTS

We have performed extensive simulations in NS-2 and for comparison purpose, we compared PRACB with three other relevant schemes. We have compared our proposed scheme



(a) (b)

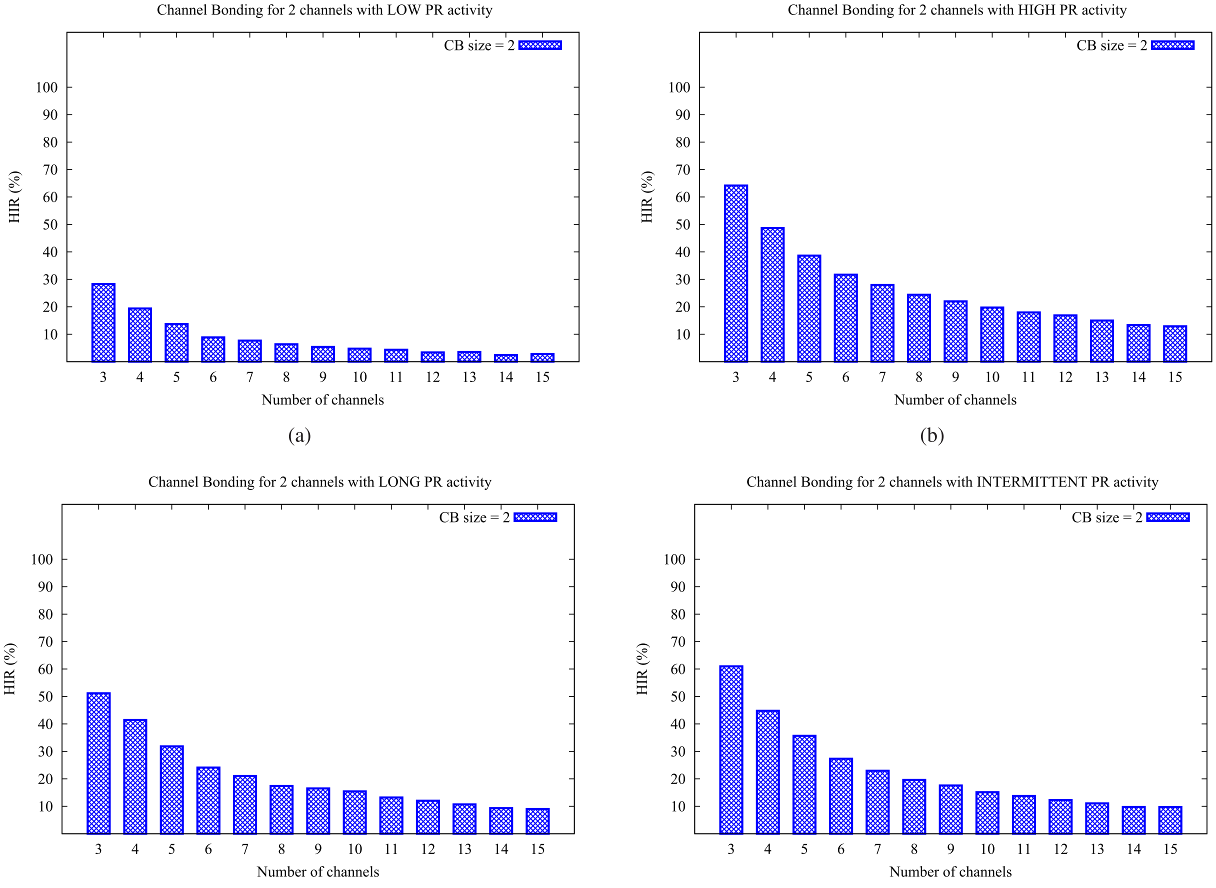
FIGURE 1. **(a) Obtaining 2 contiguous channels for channel bonding. (b) Obtaining 3 contiguous channels for channel bonding.**



(a) (b) (c) (d)

FIGURE 2. **Obtaining 2 contiguous channels for channel bonding with: (a) Low PR Activity. (b) High PR Activity. (c) Long PR Activity. (d) Intermittent PR Activity.**

with sample width algorithm (SWA) [20], cognitive radio networks over white spaces (KNOWS) [56] and AGILE [57]. The concept of SWA for CB is similar with scheme discussed in [22]. SWA does not considers any PR activity and performs channel bonding by changing channel width whenever required. KNOWS gives the implementation of channel width adaptation over white spaces utilizing the TV band for unlicensed operations. It cooperatively detects and shares the vacant bands for unlicensed users, whereas, AGILE dynamically tunes a node to the channel central frequency and



(a) (b)

(c) (d)

FIGURE 3. **Harmful interference avoided for 2 Contiguous channels with: (a) Low PR Activity. (b) High PR Activity. (c) Long PR Activity. (d) Intermittent PR Activity.**

bandwidth to use the under-utilize channels in commercial WLAN deployment. All these three schemes i.e. SWA, KNOWS, and AGILE have following common properties which make our proposed scheme PRACB different from them.

- All these three schemes are performing channel bonding or adapting the width of the channel but they are not doing it intelligently. For instance, these schemes are not considering the channel bonding size while performing channel bonding dynamically.
- These schemes are not considering PR activity while bonding the channels. In PRACB, we check PR activity while making a bond and select those channels which are free from PR activity. If a PR node appears on a channel during CR transmission, the PRACB will break the bond to avoid PR-CR interference and will find other vacant contiguous channels.

In summary, we compare PRACB with (a) SWA, which was designed for CB in wireless networks, (b) KNOWS, which was designed for CB in cognitive radio networks, and (c) AGILE, which was designed for CB in commercial 802.11 WLAN deployments.

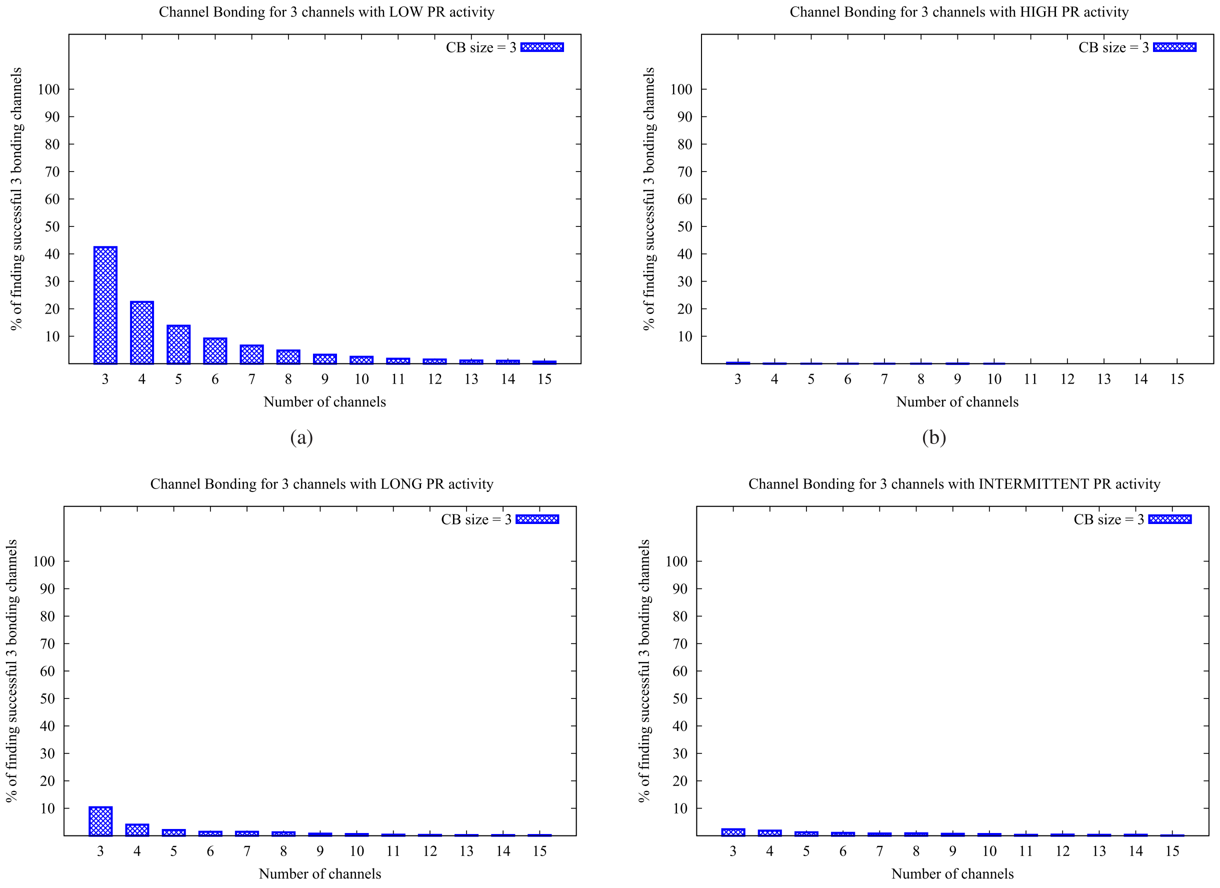
We have used aodv protocol at network layer and maccon protocol at link layer. We have increased the total number of channels from 2 to 15 and run our simulation for 10000 seconds. By these parameters, we have calculated harmful interference ratio (HIR) with PR nodes, the results revealed that PRACB out marked the other scheme and minimum HIR occurred with PR nodes when using PRACB.

Let "T_o" is total number of times channel is occupied by PR nodes, "D_r" is total number of times the packet dropped due to PR activity and "N" is total number of times channel decision occur. Then the harmful interference (HIR) can be calculated as:

$$HIR = \frac{T_o - D_r}{N} \tag{8}$$

The delivery ratio (DR) is an important performance metric which estimates that how many transmitted packets reach the destination node. Let, "R" is the total number of packets received on selected bonded channel and "S" be the total number of packets sent then the delivery ratio (DR) can be calculated as:

$$DR = \frac{R}{S} \tag{9}$$



(a) (b) (c) (d)

FIGURE 4. **Obtaining 3 contiguous channels for channel bonding with: (a) Low PR Activity. (b) High PR Activity. (c) Long PR Activity. (d) Intermittent PR Activity.**

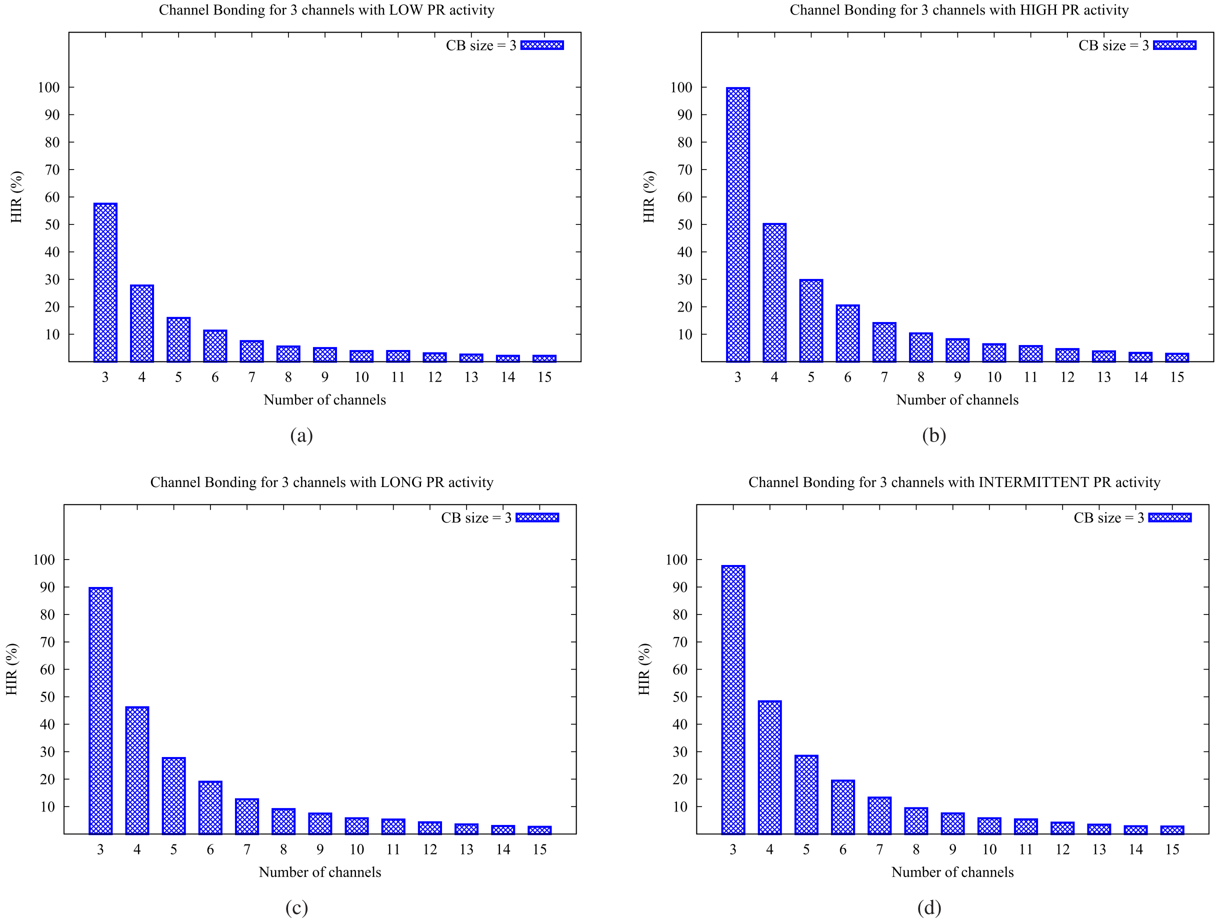
C. PROBABILITY OF FINDING CONTIGUOUS CHANNELS

In Fig. 1(a), we have set the value of bond size as 2. There are total 15 available channels and out of these 15 channels, we select 2 channels randomly for each case. We start from 2 channels in the network and then gradually increase them to 15. When there are 2 channels, there is 100% occurrence of finding contiguous channels both at sender and receiver as there is no third channel and all two channels are contiguous. Here it is important to mention that we are randomly selecting the channels and have formulated our design in such a way that it does not selects a channel twice. When channels are increased gradually, the percentage of finding contiguous channels decreases as there exist non-contiguous channels in the same set. Now, when there are 3 channels available and both sender and receiver execute the CB algorithm to select 2 contiguous channels, it is quite possible that the sender selects channel 1 and channel 2 to make a bond and receiver selects channel 2 and channel 3 for bonding. The bond will be created but the packet will be dropped as sender and receiver are tuned to different channels. So, in this case, the percentage of finding successful bonding channels decreases. When total channels are increased to 15, in this situation, both sender and receiver will have 14 pairs each with bond size of 2 channels. Now sender will randomly select a bond among these 14 pairs and receiver will also select a randomly selected bonded channel pair. So, when there are 15 channels, the percentage of finding contiguous channels decreases to 13%. *Thus, we conclude that, as we increase the number of channels, the chances of obtaining contiguous channels decrease.*

When we increase the bond size as 3, we get all contiguous channels when there are total 3 channels in the available channel set as shown in Fig. 1(b). This is due to the fact that PR activity is not present over the network and all three channels which are contiguous as well get selected for bonding. However, when channels increase in available channel set, the occurrence of contiguous channels decreases. *Thus we conclude that, a big set of contiguous channels is difficult to find from multiple available channels.*

D. IMPACT OF CB ON PR ACTIVITY MODEL

When PR activity has been added to PRACB algorithm, the number of contiguous channels decrease. This is due to the reason that PRACB selects only those channels which are



(a) (b)

(c) (d)

FIGURE 5. **Harmful interference avoided for 3 Contiguous channels with: (a) Low PR Activity. (b) High PR Activity. (c) Long PR Activity. (d) Intermittent PR Activity.**

free from PR activity. As shown in Fig. 2(a), the percentage of finding contiguous channels is high with less number of channels whereas we increase the number of channels, the probability decreases. The behavior of high PR activity can be seen in Fig. 2(b), where we get very less probability of contiguous channels for bonding. The effect of long and intermittent PR activity can be seen in Fig. 2(c) and 2(d) respectively.

We can also estimate the probability of harmful interference (HIR) which will be caused if not taken care of. The HIR depends on the type of PR activity present in the network. Fig. 3(a) shows the probability of HIR caused by channel bonding algorithm having 2 contiguous channels in the presence of low PR activity. As the number of channels increase in the network, the probability of causing HIR decreases. The HIR increases when high PR activity (Fig. 3(b)) is present over the network. The effect of HIR can also be observed with long and intermittent PR activities in Fig. 3(c) and 3(d) respectively. The probability of causing HIR in Fig. 3(c) is high as compared to Fig. 3(a) because when long PR activity appears over the channels, the PR nodes stay active for long duration of time and channel cannot be utilized by CR node. When high PR activity appears on the channels, the PR nodes stay active for long duration and in-active for short duration due to which probability of causing HIR is higher in Fig. 3(b) as compared to Fig. 3(c).

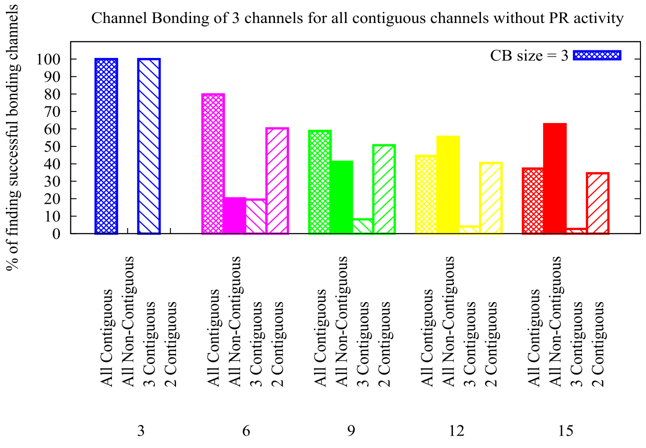
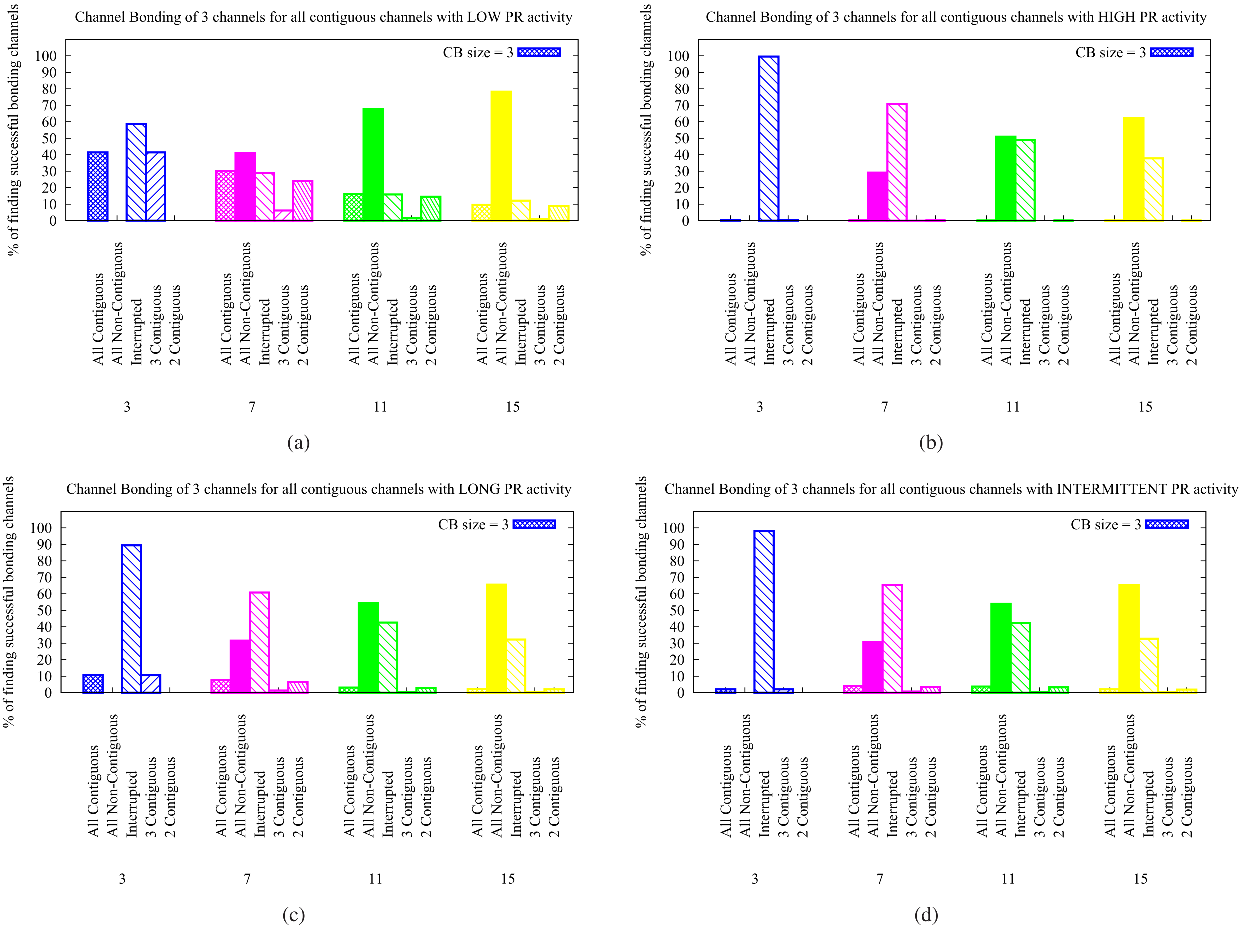


FIGURE 6. **Overview of all contiguous channels for channel bonding. All Contiguous is the combined case when algorithm finds any set of 2 or 3 contiguous channels. All Non-Contiguous is the case when there are all non-consecutive channels and not suitable for bonding. 3-Contiguous is the case when there is any set of 3 consecutive channels found in available channel set. 2-Contiguous is the case when there is any set of 2 consecutive channels found in available channel set.**



Channel Bonding of 3 channels for all contiguous channels with LOW PR activity

Channel Bonding of 3 channels for all contiguous channels with HIGH PR activity

Channel Bonding of 3 channels for all contiguous channels with LONG PR activity

Channel Bonding of 3 channels for all contiguous channels with INTERMITTENT PR activity

(a) (b) (c) (d)

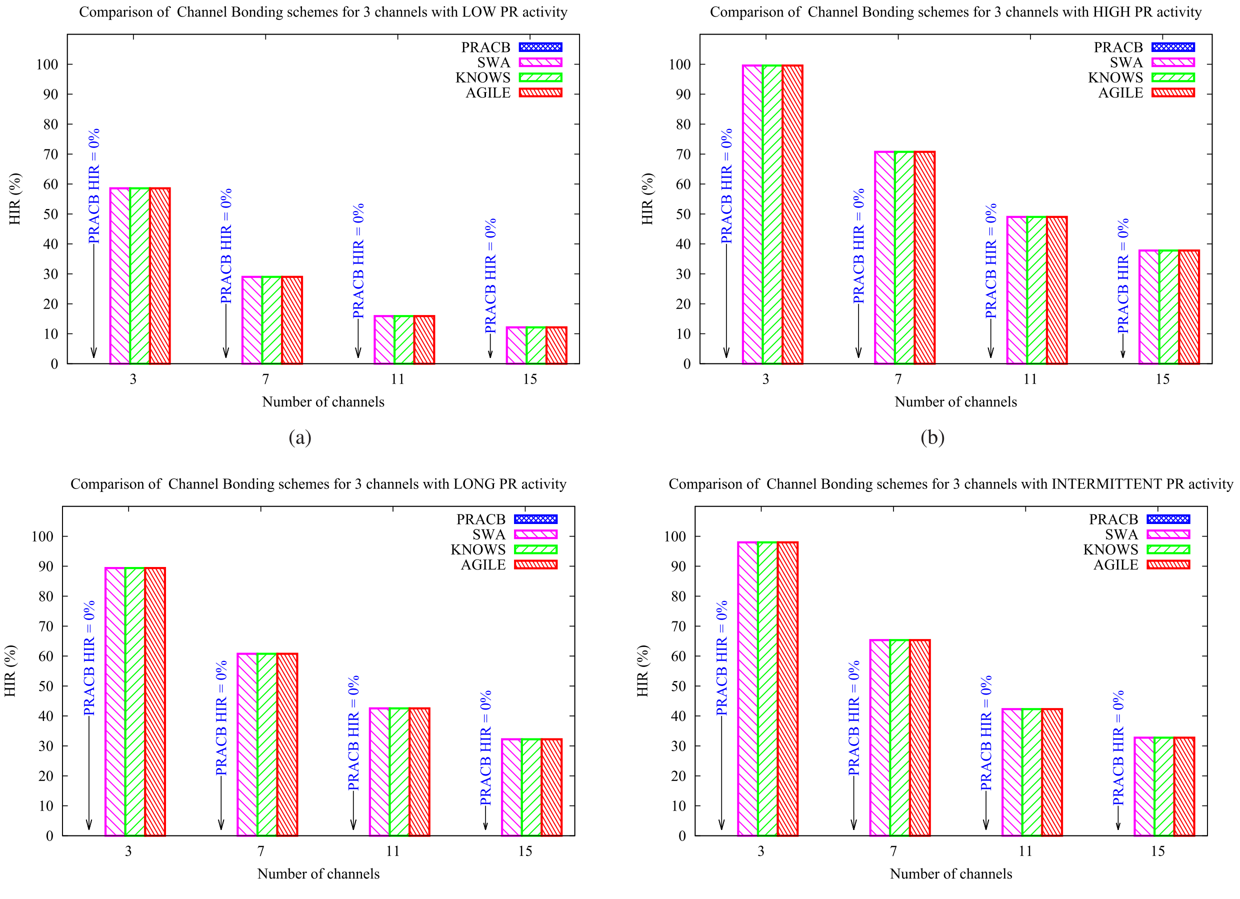
FIGURE 7. Overview of all contiguous channels for channel bonding with: (a) Low PR Activity. (b) High PR Activity. (c) Long PR Activity. (d) Intermittent PR Activity.

When CB size has been selected as 3 in presence of PR activity, the percentage of finding 3 contiguous channels for bonding decreases. It is due to the fact that low PR activity (Fig. 4(a)) have its impact over the network and only those channels are selected for bond which are free from PR activity. When the total number of channels is increased, the percentage of contiguous channels further decreases due to the reason that it is difficult to find contiguous channels from larger set of channels. As high PR activity (Fig. 4(b)) is introduced, the percentage of finding 3 contiguous channels diminishes due to all the channels occupied by PR node. Hence high PR activity is not suitable for channel bonding. The long PR activity (as shown in Fig. 4(c)) has mild behavior for channel bonding whereas, the intermittent PR activity has uneven behavior on PRACB algorithm as shown in Fig. 4(d).

The HIR caused when CB size is 3 can be seen in Fig. 5(a) when there is low PR activity present in the network. This HIR has been avoided by performing channel sensing and then selecting only those channels which are free from PR activity. The percentage of HIR increases when there is high PR activity in the network. It can be seen in Fig. 5(b) that almost all channels are occupied when there are total three channels in the network, as number of channels increases the percentage of causing HIR decreases and PRACB algorithm gets opportunity to bond the free channels. The effect of long and intermittent PR activity can also be seen on PRACB algorithm in Fig. 5(c) and 5(d) respectively.

E. COMBINED BEHAVIOR OF CB SCHEMES

If we want to observe the sub-optimal scenario, we select channel bonding size as 3 for a given set of available channels as shown in Fig. 6. After searching for 3 contiguous channels, the algorithm searches again for any 2 contiguous channels in the randomly selected set. It can be observed that it can increase the performance of a system which requires a bond of 3 channels to achieve the desired bandwidth but also can utilize a bond of 2 channels to maintain communication at lower bandwidth. It can also be noticed from Fig. 6 that by selecting bond size as 3, the system gets higher number of 2 contiguous channels as compared to selecting bond size as 2 (Fig. 1(a)). It is due to the reason that when system selects a big set of channels from available channel set, the chances of getting smaller contiguous chunks increases. It is worth



(a) (b) (c) (d)

FIGURE 8. **Comparison of Channel Bonding schemes for HIR with: (a) Low PR Activity. (b) High PR Activity. (c) Long PR Activity. (d) Intermittent PR Activity.**

mentioning here that Fig. 6 shows results in the absence of PR activity. Next we perform the analysis of this approach in the presence of PR activities.

When we introduce low PR activity in the network (Fig. 7(a)), the number of all contiguous channels decreases due to PR activity. There are no non-contiguous channels when there are total three channels present. When number of total channels is increased, the number of non-contiguous channels increases and contiguous channels decreases. The number of 3 contiguous and 2 contiguous channels have a specific behavior. When there are total three channels, all these are contiguous so all contiguous channels are equal to 3 contiguous channels. When total number of channels is increased, number of 3 contiguous channels decreases and we get more number of 2 contiguous channels as described earlier. The number of 2 contiguous channels also decrease with increase in total channels as all contiguous channels are decreasing. The interrupted channels is the case when there is PR activity present on the channels and PRACB does not selects the channels. When total number of channels increase the interrupted channels decrease as there are less chance of presence of PR activity when contiguous channels are selected from larger set of channels.

When high PR activity is present in the network, the number of interrupted channels is so large that it is highly unlikely to find the PR activity free contiguous channels. Hence, when there are total three channels in the network, almost all the channels are interrupted. As the total number of channels is increased, the number of interrupted channels decrease gradually but number of non-contiguous channels increase as shown in Fig. 7(b). Hence, high PR activity is not suitable to perform channel bonding. The effect of long and intermittent PR activity can be observed in Fig. 7(c) and 7(d).

F. COMPARISON ANALYSIS

We have performed comparison of PRACB, SWA, KNOWS and AGILE for two performance metrics, i.e. Harmful Interference Ratio (HIR) and Delivery Ratio (DR). We have applied all four PR activities and observed the behavior of both schemes.

1) HARMFUL INTERFERENCE RATIO

In case of low PR activity (as shown in Fig. 8(a)), SWA, KNOWS and AGILE select interrupted channels hence cause HIR. On the other hand, PRACB selects only those contiguous channels which are free from PR activity hence no

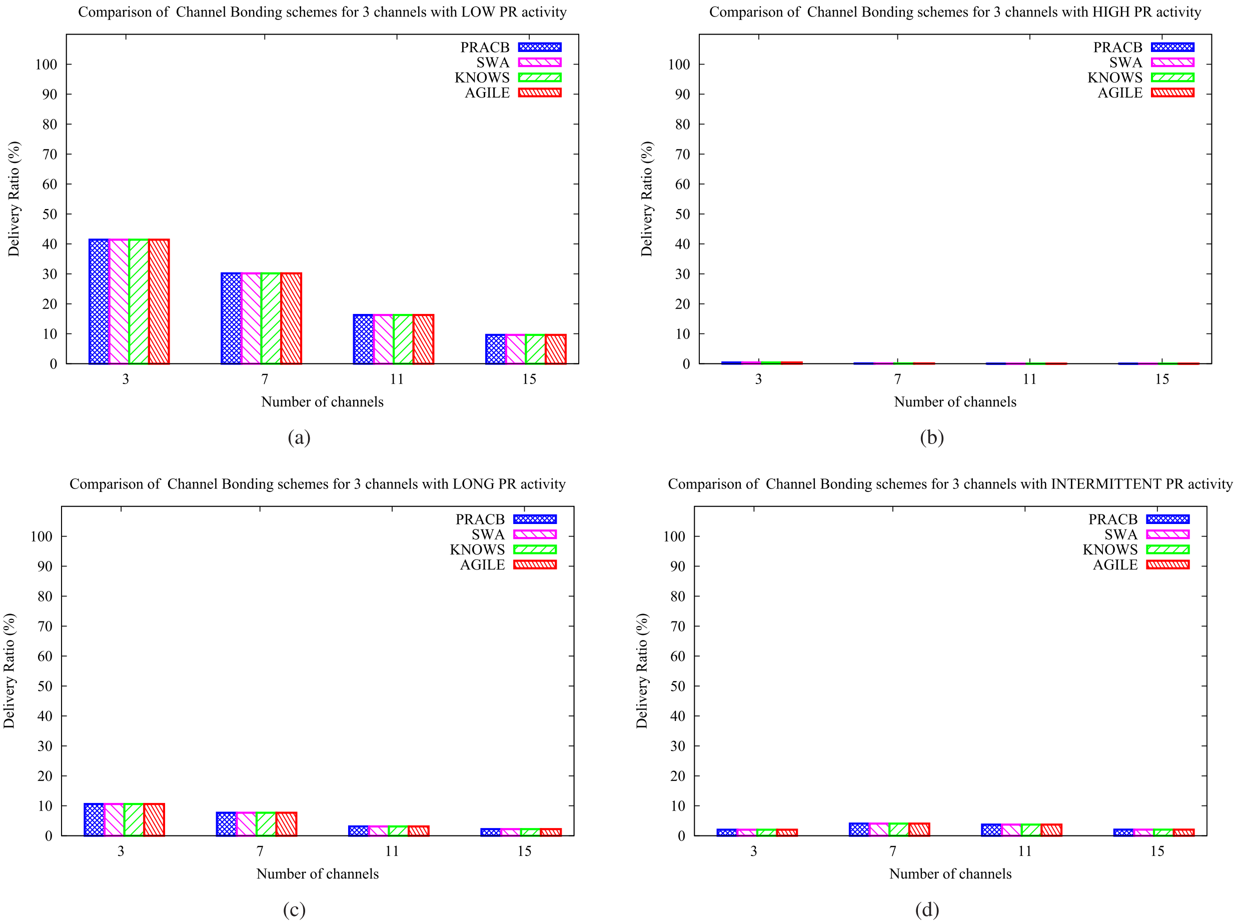


FIGURE 9. **Comparison of Channel Bonding schemes for DR with: (a) Low PR Activity. (b) High PR Activity. (c) Long PR Activity. (d) Intermittent PR Activity.**

HIR has been caused and transmission has been occurred successfully.

The case of HIR becomes more crucial when there is high PR activity present on the channels. The scheme which does not consider PR activity before channel selection i.e. SWA, KNOWS and AGILE cause huge HIR where as PRACB efficiently senses the PR activity and avoids HIR as shown in Fig. 8(b). The comparison of both schemes with long and intermittent PR activities has been shown in Fig. 8(c) and 8(c). All these results show that our proposed scheme PRACB has outperformed other schemes effectively by avoiding HIR and performing interference free bonding. *Hence we conclude that, intelligent channel bonding decisions can reduce the harmful interference to PR nodes.*

2) DELIVERY RATIO

The delivery ratio (DR) also determines the performance of any network. The DR can be observed as how many packets sent from transmitter have been received at the receiver. When there is low PR activity on the network (as shown in Fig. 9(a)), PRACB selects only those channels which are vacant hence the DR is almost 40% when there are total three channels in the network. It is noticeable that other schemes also provide almost same DR as they are selecting the channels in a similar way but they keep on transmitting packets without considering PR activity hence, creating almost 60% HIR and gets successful in transmitting the packets for only 40% time when channels were idle. All the interrupted packets are re-transmitted which causes extra traffic in the network.

The delivery ratio diminishes when high PR activity is introduced in the network as depicted in Fig. 9(b). It is due to the reason that almost all the channels are occupied by PR nodes hence PRACB does not selects those channels and keeps the transmitter silent. The SWA, KNOWS and AGILE perform worse in this case as they cause maximum HIR which in turn causes re-transmission of interrupted packets. The effect of long and intermittent PR activities on DR can be observed in Fig. 9(c) and 9(d) respectively. *Hence, though in terms of DR, PRACB gives the same result as compared to SWA, KNOWS and AGILE but in terms of HIR, PRACB outperforms all these schemes. This is the main point where PRACB outperforms other schemes.*

V. CONCLUSION AND FUTURE WORK

In this paper, we have proposed a scheme of channel bonding which utilizes the white spaces hence, satisfies the requirement of CR nodes in CRSN. Extensive simulations show that

TABLE 3. Wireless channel parameters used in simulation (Low PR Activity).

	Ch 0	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9	Ch 10	Ch 11	Ch 12	Ch 13	Ch 14
T_{ON}	0.83	0.77	0.42	0.31	0.53	0.27	0.36	0.2	0.26	0.24	0.13	0.15	0.18	0.48	0.3
T_{OFF}	2.5	1.11	10.0	1.67	3.33	10.0	4.0	9.09	3.45	2.08	5.26	3.7	1.0	1.61	2.63
λ_X	1.20	1.29	2.38	3.22	1.88	3.70	2.77	5	3.84	4.16	7.69	6.66	5.55	2.08	3.33
λ_Y	0.4	0.90	0.1	0.59	0.30	0.1	0.25	0.11	0.28	0.48	0.19	0.27	1	0.62	0.38
μ^i	0.24	0.40	0.04	0.15	0.13	0.02	0.08	0.02	0.07	0.10	0.02	0.03	0.15	0.22	0.10

TABLE 4. Wireless channel parameters used in simulation (High PR Activity).

	Ch 0	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9	Ch 10	Ch 11	Ch 12	Ch 13	Ch 14
T_{ON}	3.33	1.11	10.0	5.0	2.5	1.67	2.86	5.56	5.88	4.35	1.85	1.3	1.0	1.23	2.38
T_{OFF}	0.83	0.77	0.42	0.31	0.53	0.27	0.36	0.2	0.26	0.24	0.13	0.15	0.18	0.48	0.3
λ_X	0.30	0.90	0.1	0.2	0.4	0.59	0.34	0.17	0.17	0.22	0.54	0.76	1	0.81	0.42
λ_Y	1.20	1.29	2.38	3.22	1.88	3.70	2.77	5	3.84	4.16	7.69	6.66	5.55	2.08	3.33
μ^i	0.80	0.59	0.95	0.94	0.82	0.86	0.88	0.96	0.95	0.94	0.93	0.89	0.84	0.71	0.88

TABLE 5. Wireless channel parameters used in simulation (Long PR Activity).

	Ch 0	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9	Ch 10	Ch 11	Ch 12	Ch 13	Ch 14
T_{ON}	3.33	1.11	10.0	5.0	2.5	1.67	2.86	5.56	5.88	4.35	1.85	1.3	1.0	1.23	2.38
T_{OFF}	2.5	1.11	10.0	1.67	3.33	10.0	4.0	9.09	3.45	2.08	5.26	3.7	1.0	1.61	2.63
λ_X	0.30	0.90	0.1	0.2	0.4	0.59	0.34	0.17	0.17	0.22	0.54	0.76	1	0.81	0.42
λ_Y	0.4	0.90	0.1	0.59	0.30	0.1	0.25	0.11	0.28	0.48	0.19	0.27	1	0.62	0.38
μ^i	0.57	0.5	0.5	0.74	0.42	0.14	0.41	0.37	0.63	0.67	0.26	0.26	0.5	0.43	0.47

TABLE 6. Wireless channel parameters used in simulation (Intermittent PR Activity).

	Ch 0	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9	Ch 10	Ch 11	Ch 12	Ch 13	Ch 14
T_{ON}	0.83	0.77	0.42	0.31	0.53	0.27	0.36	0.2	0.26	0.24	0.13	0.15	0.18	0.48	0.3
T_{OFF}	0.27	0.36	0.2	0.26	0.24	0.83	0.77	0.42	0.31	0.53	0.4	0.29	0.15	0.53	0.2
λ_X	1.20	1.29	2.38	3.22	1.88	3.70	2.77	5	3.84	4.16	7.69	6.66	5.55	2.08	3.33
λ_Y	3.70	2.77	5	3.84	4.16	1.20	1.29	2.38	3.22	1.88	2.5	3.44	6.66	1.88	5
μ^i	0.75	0.68	0.67	0.54	0.68	0.24	0.31	0.32	0.45	0.31	0.24	0.34	0.54	0.47	0.6

proposed scheme outperforms by providing PR-CR interference free communication. Our scheme also helps in maintaining the highest possible delivery ratio between two communicating nodes through channel bonding while minimizing the re-transmissions in the network. As plan of our future work, we will use the proposed CB algorithm in conjunction with any routing protocol.

Appendix

See Tables 3–6.

REFERENCES

[1] I. F. Akyildiz and M. C. Vuran, *Wireless Sensor Networks*. Hoboken, NJ, USA: Wiley, 2010.

[2] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "A survey on spectrum management in cognitive radio networks," *IEEE Commun. Mag.*, vol. 46, no. 4, pp. 40–48, Apr. 2008.

[3] A. M. K. Kavi Khedo and R. Perseedoss, "A wireless sensor network air pollution monitoring system," *Int. J. Wireless Mobile Netw.*, vol. 2, no. 2, pp. 31–45, 2010.

[4] B. Rashid and M. H. Rehmani, "Applications of wireless sensor networks for urban areas: A survey," *J. Netw. Comput. Appl.*, vol. 60, pp. 192–219, Jan. 2016.

[5] M. Z. A. Bhuiyan, G. Wang, and A. V. Vasilakos, "Local area prediction-based mobile target tracking in wireless sensor networks," *IEEE Trans. Comput.*, vol. 64, no. 7, pp. 1968–1982, Jul. 2015.

[6] J. Yick, B. Mukherjee, and D. Ghosal, "Wireless sensor network survey," *Comput. Netw.*, vol. 52, no. 12, pp. 2292–2330, Aug. 2008.

[7] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Comput. Netw.*, vol. 38, no. 4, pp. 393–422, 2002.

[8] O. B. Akan, O. Karli, and O. Ergul, "Cognitive radio sensor networks," *IEEE Netw.*, vol. 23, no. 4, pp. 34–40, Jul./Aug. 2009.

[9] A. Ahmad, S. Ahmad, M. H. Rehmani, and N. Ul Hassan, "A survey on radio resource allocation in cognitive radio sensor networks," *IEEE Commun. Surveys Tut.*, vol. 17, no. 2, pp. 888–917, 2nd Quart., 2015.

[10] Y. Saleem and M. H. Rehmani, *Cognitive Radio Sensor Networks*. Hershey, PA, USA: IGI-Global, 2015.

[11] I. F. Akyildiz, B. F. Lo, and R. Balakrishnan, "Cooperative spectrum sensing in cognitive radio networks: A survey," *Phys. Commun.*, vol. 4, no. 1, pp. 40–62, Mar. 2011.

[12] S. Pollin, "Coexistence and dynamic sharing in cognitive radio networks," in *Cognitive Wireless Communication Networks*. New York, NY, USA: Springer, 2007, pp. 79–113.

[13] D. J. Schmidt, "Cellular channel bonding for improved data transmission," U.S. Patent 7 020 472 B2, Mar. 28, 2006.

[14] Y. Lu, H. He, J. Wang, and S. Li, "Opportunistic spectrum access with channel bonding," in *Proc. 4th Int. Conf. Commun. Netw. China*, 2009, pp. 1–5.

[15] Y. Rui, P. Cheng, M. Li, Q. T. Zhang, and M. Guizani, "Carrier aggregation for lte-advanced: Uplink multiple access and transmission enhancement features," *IEEE Wireless Commun.*, vol. 20, no. 4, pp. 101–108, Aug. 2013.

[16] H. Lee, S. Vahid, and K. Moessner, "A survey of radio resource management for spectrum aggregation in LTE-advanced," *IEEE Commun. Surveys Tut.*, vol. 16, no. 2, pp. 745–760, 2nd Quart., 2014.

[17] Z. Khan, H. Ahmadi, E. Hossain, M. Coupechoux, L. A. Dasilva, and J. J. Lehtomäki, "Carrier aggregation/channel bonding in next generation cellular networks: Methods and challenges," *IEEE Netw.*, vol. 28, no. 6, pp. 34–40, Nov. 2014.

[18] R. Gummadi, R. Patra, H. Balakrishnan, and E. Brewer, "Interference avoidance and control," in *Proc. Hot Topics Netw. HotNets*, 2008, pp. 13–18.

[19] T. Moscibroda, R. Chandra, Y. Wu, S. Sengupta, P. Bahl, and Y. Yuan, "Load-aware spectrum distribution in wireless LANs," in *Proc. Int. Conf. Netw. Protocols*, 2008, pp. 137–146.

[20] R. Chandra, R. Mahajan, J. Moscibroda, R. Raghavendra, and P. Bahl, "A case for adapting channel width in wireless networks," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 38, no. 4, pp. 135–146, 2008.

[21] H. S. Chiu, K. L. Yeung, and K.-S. Lui, "J-CAR: An efficient joint channel assignment and routing protocol for IEEE 802.11-based multi-channel multi-interface mobile Ad Hoc networks," *IEEE Trans. Wireless Commun.*, vol. 8, no. 4, pp. 1706–1715, May 2009.

[22] L. Deek, E. Garcia-Villegas, E. Belding, S.-J. Lee, and K. Almeroth, "The impact of channel bonding on 802.11n network management," in *Proc. 7th Conf. Emerg. Netw. Experim. Technol.*, 2011, pp. 1–11.

[23] L. Xu, K. Yamamoto, and S. Yoshida, "Performance comparison between channel-bonding and multi-channel CSMA," in *Proc. Wireless Commun. Netw. Conf.*, Mar. 2007, pp. 406–410.

[24] H. Rahul, N. Kushman, D. Katabi, C. Sodini, and F. Edalat, "Learning to share: Narrowband-friendly wideband networks," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 38, no. 4, pp. 147–158, 2008.

[25] P. Steenkiste, D. Sicker, G. Minden, and D. Raychaudhuri "Future directions in cognitive radio network research," *Proc. NSF Workshop Rep.*. vol. 4. no. 1. pp. 1–2, 2009.

[26] A. Popescu, "Cognitive radio networks," in *Proc. 9th Int. Conf. Commun.*, 2012, pp, pp. 11–15.

[27] S. Joshi, P. Pawelczak, D. Cabric, and J. Villasenor, "When channel bonding is beneficial for opportunistic spectrum access networks," *IEEE Trans. Wireless Commun.*, vol. 11, no. 11, pp. 3942–3956, Nov. 2012.

[28] H. A. B. Salameh, M. Krunz, and D. Manzi, "Spectrum bonding and aggregation with guard-band awareness in cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 3, pp. 569–581, Mar. 2014.

[29] I. F. Akyildiz, T. Melodia, and K. R. Chowdury, "Wireless multimedia sensor networks: A survey," *IEEE Wireless Commun.*, vol. 14, no. 8, pp. 32–39, Dec. 2007.

[30] M. H. Rehmani, S. Lohier, and A. Rachedi, "Channel bonding in cognitive radio wireless sensor networks," in *Proc. IEEE Int. Conf. Sel. Topics Mobile Wireless Netw. (iCOST)*, Jul. 2012, pp. 72–76.

[31] Z. Lin, M. Ghosh, and A. Demir, "A comparison of MAC aggregation vs. PHY bonding for WLANs in TV white spaces," in *Proc. 24th Int. Symp. Pers., Indoor Mobile Radio Commun., MAC Cross-Layer Design Track*, Sep. 2013, pp. 1829–1834.

[32] S. H. R. Bukhari, M. H. Rehmani, and S. Siraj, "A survey of channel bonding for wireless networks and guidelines of channel bonding for futuristic cognitive radio sensor networks," *IEEE Commun. Surveys Tut.*, vol. 18, no. 2, pp. 924–948, 2nd Quart., 2016.

[33] V. Valenta, R. Maršálek, G. Baudoin, M. Villegas, M. Suarez, and F. Robert, ''Survey on spectrum utilization in europe: Measurements, analyses and observations,'' in *Proc. 5th Int. Conf. Cognit. Radio Oriented Wireless Netw. Commun.*, 2010, pp. 1–5.

[34] S. Anand, S. Sengupta, K. Hong, K. P. Subbalakshmi, R. Chandramouli, and H. Cam, ''Exploiting channel fragmentation and aggregation/bonding to create security vulnerabilities,'' *IEEE Trans. Veh. Technol.*, vol. 63, no. 8, pp. 3867–3874, Oct. 2014.

[35] V. Gardellin, S. K. Das, and L. Lenzini, ''Self-coexistence in cellular cognitive radio networks based on the IEEE 802.22 standard,'' *IEEE Wireless Commun.*, vol. 20, no. 2, pp. 52–59, Apr. 2013.

[36] L. Deek, E. Garcia-Villegas, E. Belding, S.-J. Lee, and K. Almeroth, ''Intelligent channel bonding in 802.11n WLANs,'' *IEEE Trans. Mobile Comput.*, vol. 13, no. 6, pp. 1242–1255, Jun. 2014.

[37] S.-H. Kim and Y.-B. Ko, ''Wireless bonding for maximizing throughput in multi-radio mesh networks,'' in *Proc. Int. Conf. Pervasive Comput. Commun. Workshops (PerComW)*, 2007, pp. 570–576.

[38] L. Jiao, V. Pla, and F. Y. Li, ''Analysis on channel bonding/aggregation for multi-channel cognitive radio networks,'' in *Proc. Eur. Wireless Conf.*, 2010, pp. 468–474.

[39] O. D. Incel, ''A survey on multi-channel communication in wireless sensor networks,'' *Comput. Netw.*, vol. 55, no. 13, pp. 3081–3099, 2011.

[40] G. Yuan, R. C. Grammenos, Y. Yang, and W. Wang, ''Performance analysis of selective opportunistic spectrum access with traffic prediction,'' *IEEE Trans. Veh. Technol.*, vol. 59, no. 4, pp. 1949–1959, May 2010.

[41] A. W. Min and K. G. Shin, ''Exploiting multi-channel diversity in spectrum-agile networks,'' in *Proc. INFOCOM*, 2008.

[42] H. Kim and K. G. Shin, ''Fast discovery of spectrum opportunities in cognitive radio networks,'' in *Proc. IEEE DySPAN*, Oct. 2008, pp. 1–12.

[43] O. Mehanna, A. Sultan, and H. El Gamal, ''Cognitive MAC protocols for general primary network models,'' Dept. Comput. Sci., Cornell Univ., Ithaca, NY, USA, Tech. Rep. #0907.4031, 2009.

[44] A. S. Zahmati, X. Fernando, and A. Grami, ''Steady-state Markov chain analysis for heterogeneous cognitive radio networks,'' in *Proc. Sarnoff*, 2010, pp. 1–5.

[45] L. Yang, L. Cao, and H. Zheng, ''Proactive channel access in dynamic spectrum networks,'' *Phys. Commun.*, vol. 1, no. 2, pp. 103–111, 2008.

[46] A. Adas, ''Traffic models in broadband networks,'' *IEEE Commun. Mag.*, vol. 35, no. 7, pp. 82–89, Jul. 1997.

[47] B. Vujičić, N. Cackov, S. Vujičić, and L. Trajković, ''Modeling and characterization of traffic in public safety wireless networks,'' in *Proc. SPECTS*, 2005, pp. 1–10.

[48] H. Kim and K. G. Shin, ''Efficient discovery of spectrum opportunities with MAC-layer sensing in cognitive radio networks,'' *IEEE Trans. Mobile Comput.*, vol. 7, no. 5, pp. 533–545, May 2008.

[49] K. Sriram and W. Whitt, ''Characterizing superposition arrival processes in packet multiplexers for voice and data,'' *IEEE J. Sel. Areas Commun.*, vol. 4, no. 6, pp. 833–846, Sep. 1986.

[50] M. H. Rehmani, A. C. Viana, H. Khalife, and S. Fdida, ''SURF: A distributed channel selection strategy for data dissemination in multi-hop cognitive radio networks,'' *Comput. Commun.*, vol. 36, nos. 10–11, pp. 1172–1185, 2013.

[51] T. Yucek and H. Arslan, ''A survey of spectrum sensing algorithms for cognitive radio applications,'' *IEEE Commun. Surveys Tut.*, vol. 11, no. 1, pp. 116–130, 1st Quart., 2009.

[52] A. Ghasemi and E. S. Sousa, ''Optimization of spectrum sensing for opportunistic spectrum access in cognitive radio networks,'' in *Proc. 4th IEEE Consum. Commun. Netw. Conf.*, Jan. 2007, pp. 1022–1026.

[53] W. Y. Lee and I. F. Akyildiz, ''Optimal spectrum sensing framework for cognitive radio networks,'' *IEEE Trans. Wireless Commun.*, vol. 7, no. 10, pp. 3845–3857, Oct. 2008.

[54] A. Aijaz, S. Ping, M. R. Akhavan, and A.-H. Aghvami, ''CRB-MAC: A receiver-based MAC protocol for cognitive radio equipped smart grid sensor networks,'' *IEEE Sensors J.*, vol. 14, no. 12, pp. 4325–4333, Dec. 2014.

[55] (2013). *Cognitive Radio Cognitive Network Simulator*. [Online]. Available: http://faculty.uml.edu/TriciaChigan/Research/CRCNSimulator.htm

[56] Y. Yuan *et al.*, ''KNOWS: Cognitive radio networks over white spaces,'' in *Proc. Int. Sump. New Frontiers Dyn. Spectr. Access Netw.*, 2007, pp. 416–427.

[57] S. Keranidis, K. Chounos, T. Korakis, I. Koutsopoulos, and L. Tassiulas, ''Demo: Enabling AGILE spectrum adaptation in commercial 802.11 WLAN deployments,'' in *Proc. 20th Annu. Int. Conf. Mobile Comput. Netw.*, 2014, pp. 295–298.

SYED HASHIM RAZA BUKHARI received the B.Eng. degree in computer engineering from the COMSATS Institute of Information Technology (CIIT), Wah Cantt, Pakistan, in 2007, and the M.S degree from the University of Engineering and Technology, Taxila, Pakistan, in 2011. He is currently pursuing the Ph.D degree with CIIT, Wah Cantt, and an Assistant Professor with CIIT Attock, Pakistan. His research interests include the issues in wireless sensor networks with dynamic spectrum access, cognitive radio networks, and ad hoc networks. He is currently serving as a Reviewer of the *E*lsevier Pervasive and Mobile Computing journal, the *E*lsevier Computers and Electrical Engineering journal, the IEEE Access journal, the *I*EEE Communication Magazine, the *S*pringer Wireless Networks journal, and the *A*d Hoc Sensor Wireless Networks journal.

SAJID SIRAJ is currently a developer-turned academic with years of experience as a System Analyst and more recently as a Decision Scientist. His interests lie in data and decisions. He is also an active member of the Center for Decision Research at Leeds, and his software for structured decision making has been downloaded all around the world. His software and proposed methods have been used for policy making in a number of countries, and has also been used for pedagogical and investigative purposes.

MUBASHIR HUSAIN REHMANI (M'15–SM'16) received the B.Eng. degree in computer systems engineering from the Mehran University of Engineering and Technology, Jamshoro, Pakistan, in 2004, the M.S. degree from the University of Paris XI, Paris, France, in 2008, and the Ph.D. degree from University Pierre and Marie Curie, Paris, France, in 2011. He was a Post-Doctoral Fellow with the University of Paris-Est, France, in 2012. He is currently an Assistant Professor with the COMSATS Institute of Information Technology, Wah Cantonment, Pakistan. His research interests include cognitive radio ad hoc networks, smart grid, wireless sensor networks, and mobile ad hoc networks. He served in the TPC for the IEEE ICC 2015, the IEEE WoWMoM 2014, the IEEE ICC 2014, the ACM CoNEXT Student Workshop 2013, the IEEE ICC 2013, and the IEEE IWCMC 2013 conferences. He is also an Editor of the IEEE Communications Surveys and Tutorials and an Associate Editor of the *I*EEE Communications Magazine, the IEEE Access, *C*omputers and Electrical Engineering (Elsevier), the *J*ournal of Network and Computer Applications (Elsevier), the *A*d Hoc Sensor Wireless Networks, the *W*ireless Networks (Springer) journal, and the *J*ournal of Communications and Networks. He is also serving as a Guest Editor of the *A*d Hoc Networks (Elsevier), the *F*uture Generation Computer Systems (Elsevier), the IEEE Transactions on Industrial Informatics, the IEEE ACCESS, the *P*ervasive and Mobile Computing (Elsevier), and the *C*omputers and Electrical Engineering (Elsevier). He has authored two books by IGI Global, USA, one book published by CRC Press, USA, and one book is in progress with Wiley, U.K. He is the Founding Member of the IEEE Special Interest Group on Green and Sustainable Networking and Computing with Cognition and Cooperation. He received the certificate of appreciation, ''Exemplary Editor of the IEEE Communications Surveys and Tutorials for the year 2015'' from the IEEE Communications Society.

• • •