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Review Article

Spectrum Leasing in Cognitive Radio Networks: A Survey

Aqeel Raza Syed and Kok-Lim Alvin Yau

Department of Computer Science and Networked System, Sunway University, No. 5 Jalan Universiti, Bandar Sunway, 46150 Petaling Jaya, Selangor, Malaysia

Correspondence should be addressed to Aqeel Raza Syed; 12010591@imail.sunway.edu.my

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Cognitive Radio (CR) is a dynamic spectrum access approach, in which unlicensed users (or secondary users, SUs) exploit the underutilized channels (or white spaces) owned by the licensed users (or primary users, PUs). Traditionally, SUs are oblivious to PUs, and therefore the acquisition of white spaces is not guaranteed. Hence, a SU must vacate its channel whenever a PU reappears on it in an unpredictable manner, which may affect the SUs' network performance. Spectrum leasing has been proposed to tackle the aforementioned problem through negotiation between the PU and SU networks, which allows the SUs to acquire white spaces for a guaranteed period of time. Through spectrum leasing, the PUs and SUs enhance their network performances, and additionally PUs maximize their respective monetary gains. Numerous research efforts have been made to investigate the CR, whereas the research into spectrum leasing remains at its infancy. In this paper, we present a comprehensive review on spectrum leasing schemes in CR networks by highlighting some pioneering approaches and discuss the gains, functionalities, characteristics, and challenges of spectrum leasing schemes along with the performance enhancement in CR networks. Additionally, we discuss various open issues in order to spark new interests in this research area.

1. Introduction

Cognitive Radio (CR) network, which is the next-generation wireless network, aims to improve the efficiency of spectrum utilization through dynamic spectrum access. There are two categories of users, namely, primary users (PUs) and secondary users (SUs). Traditionally in CR networks, the PUs are the licensed users, and they have exclusive right to use their respective channels, while SUs are the unlicensed users, and they use the underutilized channels (or white spaces) opportunistically whenever PUs are not transmitting any packets. Hence, PUs are oblivious of the presence of SUs. There are two main challenges associated with the traditional CR Networks (CRNs) that adopt the opportunistic channel access approach. Firstly, the unpredictable PUs' activities at any given time can significantly degrade SUs' network performance (e.g., throughput and end-to-end delay) [1–4]. Secondly, channel sensing [1], which is one of the main functions in the traditional CRNs, may require SUs to exchange channel sensing outcomes among themselves, and this incurs high amount of communication overhead resulting in higher energy consumption and packet latency [5]. In addition to the traditional CRNs [2, 3], there have been research activities in the area of CR sensor networks [4]. CR sensor networks are the next-generation wireless sensor networks that exploit white spaces through dynamic spectrum access.

Spectrum leasing is a dynamic spectrum access technique in which PUs and SUs form a partnership for mutual benefits. In spectrum leasing, the SUs negotiate with PUs and acquire their white spaces [6], while the PUs lease their channels and receive rewards in the form of monetary gain or network performance enhancement through packet forwarding by SUs [7]. Hence, PUs are fully aware of the presence of SUs. Figure 1 presents a taxonomy of spectrum leasing, which covers its advantages, functionalities, characteristics, and challenges. Further descriptions about the taxonomy are found in the rest of this section, as well as Sections 2, 3, and 4, respectively. Generally speaking, with the use of spectrum leasing, PUs and SUs receive the following advantages represented by (A1) and (A2) (see Figure 1), respectively.

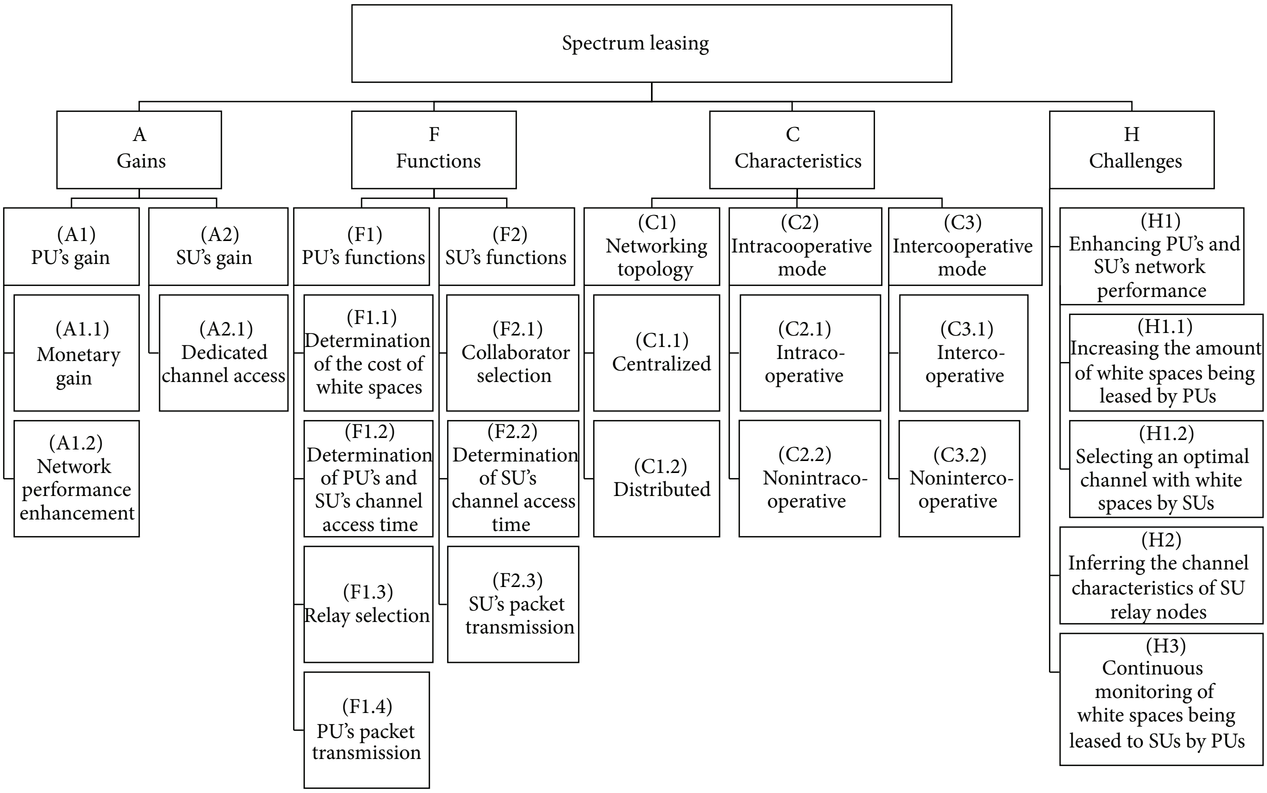

Figure 1: Taxonomy of spectrum leasing in CRNs.

(A1) *PU's Gain*

(A1.1) *Monetary Gain*. PUs may lease its licensed channels during idle periods for financial reward or revenue. For instance, Jayaweera et al. [6] propose a PU's utility function based on its monetary gain (e.g., the price set by PUs of white spaces).

(A1.2) *Network Performance Enhancement*. The PU links may deteriorate due to shadowing and interference. Through spectrum leasing, one or more SUs form an alternative route and relay PUs' traffic, and this enhances the PUs' network performance, such as successful transmission rate, throughput, end-to-end delay, and energy efficiency [8].

(A2.1) *Dedicated Channel Access*. The SUs access white spaces allocated by PUs. Subsequently, this enhances the SUs' throughput performance. Since spectrum leasing enhances the throughput performance of PUs (A1.2), it reduces the transmission time of PUs, therefore leaving more white spaces and transmission opportunities to SUs for dedicated access [9].

The advantages motivate PUs and SUs to participate in spectrum leasing. For instance, in [5], spectrum leasing maximizes a weighted sum of PUs' and SUs' throughput performance.

This paper provides an extensive survey on existing spectrum leasing schemes in CRNs. The purposes are to establish a foundation and to spark new interests in this research area covering new kinds of CR networks such as CR sensor networks [4]. Our contributions are as follows. Sections 2, 3, and 4 present the functionalities, characteristics, and challenges, respectively. Section 5 presents various spectrum leasing schemes in CRNs. Section 6 presents performance enhancement achieved by spectrum leasing schemes. Section 7 presents open issues. Finally, we present conclusions.

2. Functionalities of Spectrum Leasing in Cognitive Radio Networks

This section discusses the functionalities of PUs and SUs for spectrum leasing in CRNs. Generally speaking, spectrum leasing is comprised of the following functionalities.

(F1) *PU's Function*

(F1.1) *Determination of the Cost of White Spaces*. PUs determine the cost (e.g., monetary price) of white spaces to be imposed on SUs.

(F1.2) *Determination of PUs' and SUs' Channel Access Time*. PUs are the rightful owners of the licensed spectrum, and so the PU Base Station (BS) may determine suitable channel access time for transmission opportunities for both PUs and

SUs. For instance, in centralized networks, the PU hosts send their respective information (e.g., idle time) to PU BS. Subsequently, the PU BS allocates transmission opportunities for PU and SU networks. In other words, the PUs determine the amount of white spaces to be leased to SUs. The objective is to maximize the network performance (e.g., throughput) of PUs and SUs [10, 11].

(F1.3) *Relay Selection*. PUs select the SUs that provide the highest gain (e.g., PU-SU links with the best-known signal-to-noise ratio (SNR)) as relays in order to maximize throughput performance.

(F1.4) *PUs' Packet Transmission*. PUs transmit their own packets to destination in order to enhance their network performance.

(F2) *SU's Function*

(F2.1) *Collaborator Selection*. SUs select the suitable PUs to collaborate with. This covers the evaluation of the gain (e.g., the amount of white spaces with sufficient SNR) and cost (resources required to relay PUs' traffics, such as energy consumption).

(F2.2) *Determination of SU's Channel Access Time*. SUs determine the amounts of white spaces, which increase with channel access time, to request from PUs based on the cost imposed by the PUs. For instance, in a Time-Division Multiple Access (TDMA) system, SUs must determine the optimal time duration in which they must involve as relay to transmit PU packets and to transmit their own packets [8].

(F2.3) *SUs' Packet Transmission*. SUs transmit packets, and this involves two phases. Firstly, the SUs relay PU packets. To ensure continuous collaboration with PUs, the SUs must achieve a certain level of network performance enhancement while relaying the PUs' packets. Secondly, the SUs transmit their own packets. Spatial reuse is possible, and so the SUs must minimize interference among themselves [12]. For instance, in centralized networks, SU BS and hosts may serve as relays to transmit PU packets, and subsequently the SU BS allocates the white spaces offered by PUs to its SU hosts fairly [10, 13].

Spectrum leasing involves several steps and message handshaking, and we describe a general procedure in Figure 2. Consider two centralized PU and SU networks, which are collocated in the same area. Several PU hosts (or SU hosts) are associated with a PU BS (or SU BS). The procedure is as follows.

Step 1. The PU hosts send information on their respective idle periods (or white spaces) to PU BS.

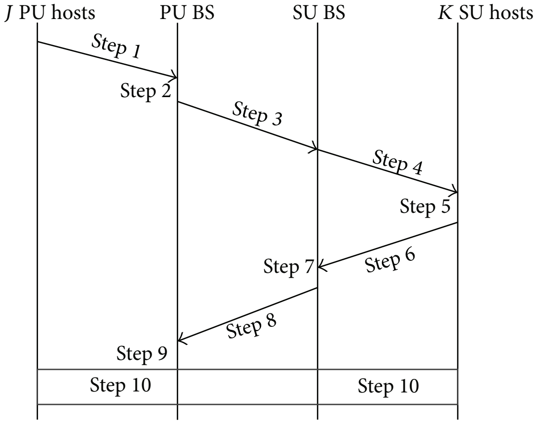

Figure 2: A general spectrum leasing procedure.

Step 2. The PU BS determines the cost (F1.1) and duration (F1.2) of white spaces. There are J PU hosts to be leased to SUs.

Step 3. The PU BS sends the cooperation information (e.g., the cost and duration, as well as SNR of the white spaces) to SU BS.

Step 4. The SU BS broadcasts the cooperation information to its SU hosts.

Step 5. The SU hosts determine the optimum transmission and relaying strategies (i.e., (F2.2) and (F2.3)) using the cooperation information. If auction mechanism is applied, the SU hosts may determine bid values.

Step 6. The SU hosts send their respective decisions (e.g., strategies and bid values) to SU BS.

Step 7. The SU BS decides to accept the lease or not and select the suitable PUs to collaborate with (F2.1).

Step 8. The SU BS sends its decisions to PU BS.

Step 9. The PU BS decides to lease or not and select the suitable SUs as relays (F1.3).

Step 10. Finally, based on the lease, the PU BS transmits its packets (F1.4) directly through a single hop, or indirectly through SU relay nodes, to the PU BS's destination node. The SU BS may divide the white spaces and assign the access time of each white space to each SU hosts (F2.2). The SUs transmit packets accordingly (F2.3).

3. Characteristics of Spectrum Leasing in Cognitive Radio Networks

This section discusses the characteristics of spectrum leasing in CRNs. There are three characteristics as follows.

(C1) *Network Topology*: *Centralized* (C1.1) and *Distributed* (C1.2). In centralized networks (C1.1), a central entity which is usually referred as Base Station (BS) is responsible for communications between PU and SU networks [14], whereas, in distributed networks (C1.2), BS does not exist, and PUs and SUs share their information through a common control channel [14]. For instance, in [5], a centralized network (C1.1) topology is used, in which PUs are leaders and responsible to select the most appropriate SU for cooperative communication and hence the SUs are followers.

(C2) *Intracooperative Mode*: *Intracooperative* (C2.1) and *Nonintracooperative* (C2.2). The PUs may cooperate among themselves through an intra-cooperative approach in order to achieve the advantages (A1.1)-(A1.2) and (A2.1). Likewise, the SUs may adopt the same approach. In Figure 3, the intracooperative (C2.1) mode is shown in (a) and (c) and from the SU's perspective, the SUs may cooperate among themselves and jointly improve network-wide performance such as throughput performance, as well as to reduce the monetary and nonmonetary spectrum leasing costs imposed by PUs. In other words, a group of SUs may lease a channel and subsequently share the channel among themselves in order to reduce spectrum leasing costs. In Figure 3, the nonintracooperative (C2.2) mode is shown in (b) and (d) and from the PU's perspective, each PU may compete with each other to lease their respective white spaces and hence each PU may set a competitive price based on the demand of channel access from SUs. From the SU's perspective, the SUs may also compete with each other to acquire the white spaces through auction-based mechanisms [15]. For instance, in [5], each SU optimizes its power allocation in the transmission of PU packets in order to fulfill the packet transmission requirements of PUs. This helps each SU to remain competitive in order to obtain white spaces in the upcoming auctions and this has been shown to improve SU throughput performance.

(C3) *Intercooperative Mode*: *Intercooperative* (C3.1) and *Nonintercooperative* (C3.2). PUs and SUs may cooperate with each other in order to achieve the advantages (A1.1)-(A1.2) and (A2.1). In Figure 3, the intercooperative (C3.1) mode is shown in (c) and (d) and the PUs and SUs cooperate with each other, and so this improves the overall network-wide performance such as throughput performance. In Figure 3, the nonintercooperative (C3.2) mode is shown in (a) and (b) and the PUs and SUs are referred to as selfish users, and they do not cooperate with each other. For instance, in [16], the PUs attempt to maximize their profit or reward out of the white spaces, while the SUs attempt to reduce their cost.

4. Challenges of Spectrum Leasing in Cognitive Radio Networks

This section discusses the challenges associated with spectrum leasing in CRNs. There are three challenges as follows.

(H1) *Increasing the Monetary Gain of PUs*. PUs aim to increase their monetary gain through spectrum leasing. This encourages the PUs to participate in spectrum leasing by increasing the amount of white spaces available to SUs. Subsequently, this increases PUs' and SUs' throughput performance [10]. The PUs may cooperate or compete with each other to lease their white spaces. As an example, in [10], PUs cooperate with each other, and linear programming is applied to set the optimal price of the white spaces in order to increase their monetary gain. As another example, in [16], PUs compete with each other, and game theory is applied to set the optimal price of the white spaces in order to increase their monetary gain.

(H2) *Selecting an Optimal Channel with White Spaces by SUs*. SUs aim to access the licensed channel or white spaces in order to increase their network performance (e.g., throughput). So, this encourages the SUs to participate in spectrum leasing and subsequently increases PUs' and SUs' network performance [17]. However, the access to white spaces by SUs requires monetary cost, and so there is a need to find an optimal channel that provides the best possible network performance while incurring the least possible cost. For instance, Cao et al. [5] propose a spectrum sharing policy in which white spaces are being leased to SUs, in order to increase the network capacity of SU network.

(H3) *Scheduling the Channel Access of PUs and SUs*. The PUs schedule the time for the transmissions of PUs' and SUs' packets in order to enhance their respective QoS performance (e.g., throughput). The time allocation for SUs' links must be sufficiently higher compared to that of PUs' links in order to reap the benefits of spectrum leasing [9]. Otherwise, the queue size at SU relay nodes may grow and eventually become insufficient to accommodate new packets from both PUs and SUs leading to packet loss. However, the white spaces being leased to SUs may not be sufficient to cater for PUs' and SUs' packets. For instance, Huang et al. [18] propose a coalition game to allocate a suitable fraction of channel access time among PUs and SUs, so that SUs transmit PUs' packets as well as their own packets.

(H4) *Continuous Monitoring of White Spaces Being Leased to SUs by PUs*. Upon negotiation, the PUs and SUs may need to monitor the white spaces (e.g., amount and channel quality) and the Quality of Service (QoS) of packet transmission in order to make sure that

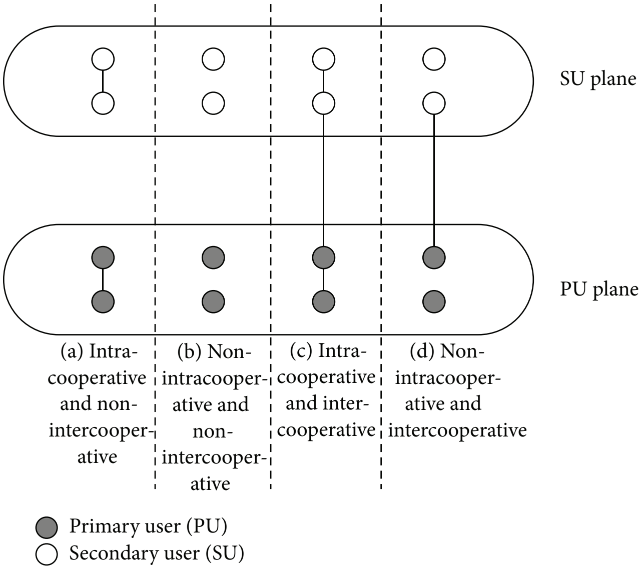

Figure 3: Mode of cooperation between PU and SU network.

each party follows suit. However, the continuous monitoring of SUs requires more intelligence to be incorporated into the PU network. For instance, in [15], PUs additionally acts as an online auctioneer to monitor the SUs activities. Likewise, in [19], PUs need to ensure that the interference caused by SUs is less than the acceptable interference level. Furthermore, SUs also need to monitor the SUs' signal level in order to reduce interference with PUs [20].

5. Spectrum Leasing Schemes in Cognitive Radio Networks

This section presents existing work on spectrum leasing schemes in CRNs. The schemes are categorized with respect to the challenges (see Section 4) and on the basis of adopted approaches (e.g., game theoretic approaches and nongame theoretic approaches) to address the challenges. The game theoretic approaches, such as Stackelberg game [21], are used to achieve the equilibrium state (e.g., Nash equilibrium [22]) and it involves PUs and SUs as players of the game. Examples of the nongame theoretic approaches are reinforcement learning [23] and convex optimization [24]. Table 1 presents the gains, functions, and characteristics of the spectrum leasing schemes. The performance enhancement achieved by each scheme is shown in Table 2 (see Section 6).

5.1. Increasing the Monetary Gain of PUs. There are six spectrum leasing schemes that focus on addressing the challenge of increasing the monetary gain of PUs that motivates the PUs to participate in spectrum leasing. These schemes have been shown to increase the monetary gain of PUs, as well as to enhance PUs' or SUs' QoS performance (e.g., throughput).

5.1.1. Schemes That Use Game Theoretic Approaches. Alptekin and Bener [16] propose one PU F(1) and one SU F(2) functionalities, namely, determination of the cost of white spaces (F1.1), as well as collaborator selection (F2.1) in order to increase PUs' monetary gain (A1.1) and to provide dedicated channel access to SUs (A2.1) in centralized (C1.1) SU networks. The purpose is to maximize the PUs' profit as seller in terms of its utility function U_p, which helps to satisfy the QoS parameters (e.g., jitter) of SUs as buyers, in the presence of J PUs and K SUs. The functionalities are modeled and solved using game theory and the Nash equilibrium in a nonintracooperative (C2.2) mode and non-intercooperative (C3.2) mode, respectively. The cumulative utility function of J PUs is defined as

$$U_p = \sum_{j=1}^{J} p_{jk} \cdot d_{jk} - c_{jk} \cdot d_{jk}, \tag{1}$$

where $j = \{1, 2, \ldots, J\}$, p_{jk} is the price that PU j imposes on SU k, d_{jk} is the demand factor (i.e., SU k's expectation on QoS requirement including jitter and throughput from PU j), and c_{jk} is the cost associated with the channel leased to SU k which must be paid by PU j to regulatory authorities (e.g., Federal Communications Commission (FCC)). The PU j determines the cost of white spaces (F1.1) and on that basis selects SU k if the difference between price p_{jk} and cost c_{jk} in PU utility function is positive, which indicates a monetary gain for PU j. The SU k selects a PU collaborator (F2.1) to achieve its QoS level as indicated in the demand factor d_{jk} while paying the PU j at the specified price p_{jk}. It has been shown that PUs are more likely to fulfill the SUs' QoS demand with the increment of price p_{jk} (i.e., monetary gain).

Lin and Fang [25] propose one PU F(1) and one SU F(2) functionalities, namely, determination of the cost of white spaces (F1.1), as well as SUs' packet transmission (F2.3) in order to increase PUs' monetary gain (A1.1) and to provide

Table 1: Gains, functions, and characteristics of the spectrum leasing schemes.

Challenges	References	(A) Gains			(F) Functions							(C) Characteristics					
		(A1) PUs Gains		(A2) SUs Gains	(F1) PUs Functions				(F2) SUs Functions			(C1) Networking topology		(C2) Intra-operative mode		(C3) Inter-operative mode	
		(A1.1) Monetary gain	(A1.2) Network performance enhancement	(A2.1) Dedicated channel access	(F1.1) Determination of the cost of white spaces	(F1.2) Determination of PUs' and SUs' channel access time	(F1.3) Relay selection	(F1.4) PUs' Packet transmission	(F2.1) Collaborator selection	(F2.2) Determination of SU's channel access time	(F2.3) SUs' Packet transmission	(C1.1) Centralized	(C1.2) Distributed	(C2.1) Intra-cooperative	(C2.2) Non-intracooperative	(C3.1) Inter-cooperative	(C3.2) Non-intercooperative
(H1) Increasing the monetary gain of PUs	(Alptekin and Bener, 2009) [16]	×		×	×				×			×			×		×
	(Lin and Fang, 2008) [25]	×		×	×						×		×		×		×
	(Yi et al., 2010) [10]	×		×	×		×	×		×	×	×		×		×	
	(Kim and Shin, 2009) [26]	×			×								×		×		×
	(Song and Lin, 2009) [13]	×		×	×						×		×		×		×
	(Wu et al., 2008) [7]	×		×	×							×		×			×
(H2) Selecting an optimal channel with white spaces by SUs	(Chan et al., 2011) [17]		×	×		×	×				×	×			×	×	
	(Vazquez-Vilar et al., 2010) [20]		×	×			×	×			×	×		×		×	
	(Cao et al., 2012) [5]		×				×	×			×	×		×		×	
	(Jayaweera et al., 2011) (centralized approach) [8]		×	×			×	×			×	×		×		×	
	(Jayaweera et al., 2011) (distributed approach) [8]		×	×			×	×			×		×		×	×	
	(Murawski and Ekici, 2011) [27]		×	×			×	×			×		×	×		×	
	(Toroujeni et al., 2011) [28]		×	×			×	×			×		×	×		×	

Table 1: Continued.

Challenges	References	(A) Gains			(F) Functions							(C) Characteristics					
		(A1) PUs Gains		(A2) SUs Gains	(F1) PUs Functions				(F2) SUs Functions			(C1) Networking topology		(C2) Intra-operative mode		(C3) Inter-operative mode	
		(A1.1) Monetary gain	(A1.2) Network performance enhancement	(A2.1) Dedicated channel access	(F1.1) Determination of the cost of white spaces	(F1.2) Determination of PUs' and SUs' channel access time	(F1.3) Relay selection	(F1.4) PUs' Packet transmission	(F2.1) Collaborator selection	(F2.2) Determination of SU's channel access time	(F2.3) SUs' Packet transmission	(C1.1) Centralized	(C1.2) Distributed	(C2.1) Intra-cooperative	(C2.2) Non-intracooperative	(C3.1) Inter-cooperative	(C3.2) Non-intercooperative
(H3) Scheduling the channel access of PUs and SUs	(Chen et al., 2011) [29]		×	×		×	×				×		×		×		×
	(Huang et al., 2011) [18]		×	×	×	×	×				×	×		×		×	
	(Wang et al., 2010) [30]		×	×	×	×		×		×	×	×		×		×	
	(Stanojev et al., 2008) [31]		×	×		×	×			×			×		×	×	
	(Wang et al., 2010) [32]		×	×		×	×				×		×		×		×
	(Zhang et al., 2010) [33]		×	×		×	×				×		×		×	×	
	(Zhu et al., 2012) [34]			×					×	×			×		×		×
	(Asaduzzaman et al., 2011) [35]		×	×		×	×	×		×		×		×		×	
	(Khalil et al., 2011) [36]		×	×		×	×	×			×	×			×	×	
	(Zhou et al., 2011) [11]	×		×	×					×	×		×	×		×	
(H4) Continuous monitoring of white spaces being leased to SUs by PUs	(Jayaweera et al., 2010) [6]			×			×				×	×			×		×
	(Jayaweera and Li, 2009) [19]			×			×				×	×			×		×
	(Hakim et al., 2010) [37]			×			×				×	×			×		×
	(Sodagari et al., 2011) [15]	×		×	×					×			×	×			×

Table 2: Performance enhancements achieved by the spectrum leasing schemes.

Challenges	References	Performance Enhancement								
		(P1) Lower outage probability	(P2) Higher outage capacity	(P3) Better QoS level	(P4) Higher energy efficiency	(P5) Higher monetary gain	(P6) Balanced tradeoff between spectrum cost and monetary gain	(P7) Balanced tradeoff between PUs' and SUs' channel access time	(P8) Better security level	(P9) Lower PUs' interference level
(H1) Increasing the monetary gain of PUs	(Alptekin and Bener, 2009) [16]			×		×	×			
	(Lin and Fang, 2008) [25]					×				
	(Yi et al., 2010) [10]			×		×				
	(Kim and Shin, 2009) [26]					×				
	(Song and Lin, 2009) [13]			×					×	
	(Wu et al., 2008) [7]					×				×
(H2) Selecting an optimal channel with white spaces by SUs	(Chan et al., 2011) [17]			×		×	×	×		
	(Vazquez-Vilar et al., 2010) [20]			×	×					
	(Cao et al., 2012) [5]			×						
	(Jayaweera et al., 2011) [8]			×	×			×		
	(Murawski and Ekici, 2011) [27]			×						
	(Toroujeni et al., 2011) [28]			×					×	
(H3) Scheduling the channel access of PUs and SUs	(Chen et al., 2011) [29]			×				×		
	(Huang et al., 2011) [18]			×			×			
	(Wang et al., 2010) [30]				×			×		
	(Stanojev et al., 2008) [31]	×		×						
	(Wang et al., 2010) [32]			×	×			×		
	(Zhang et al., 2010) [33]			×	×			×		
	(Zhu et al., 2012) [34]			×						
	(Asaduzzaman et al., 2011) [35]	×	×					×		
	(Khalil et al., 2011) [36]			×						
	(Zhou et al., 2011) [11]							×		

Table 2: Continued.

Challenges	References	Performance Enhancement								
		(P1) Lower outage probability	(P2) Higher outage capacity	(P3) Better QoS level	(P4) Higher energy efficiency	(P5) Higher monetary gain	(P6) Balanced tradeoff between spectrum cost and monetary gain	(P7) Balanced tradeoff between PUs' and SUs' channel access time	(P8) Better security level	(P9) Lower PUs' interference level
(H4) Continuous monitoring of white spaces being leased to SUs by PUs	(Jayaweera et al., 2010) [6]	×		×					×	
	(Jayaweera and Li, 2009) [19]			×					×	
	(Hakim et al., 2010) [37]	×		×	×					
	(Sodagari et al., 2011) [15]			×		×				×

dedicated channel access to SUs (A2.1) in distributed (C1.2) SU networks. The purpose is to maximize the PUs' and SUs' utility functions U_p and U_s, respectively, while taking into account the mutual benefits of PUs (or sellers) and SUs (or buyers). The functionalities are modeled in the presence of J PUs and K SUs and solved using a two-level game that is split into PU-level game and SU-level game in a non-intracooperative (C2.2) mode and non-intercooperative (C3.2) mode, respectively. In this hierarchy of games, PUs compete with each other to lease their spectrum to SUs by adjusting their price of white spaces in order to maximize their respective utility functions; each SU attempts to lease a certain amount of white spaces from PU that provides the optimal quality white spaces. The PUs' $j \in J$ utility function is defined as

$$U_{p,j} = \sum_{k=1}^{K} B_{jk} \left\{ p_{jk} - c_j \right\}, \tag{2}$$

where B_{jk} is the bandwidth (or white spaces) that PU j allocates to SU k, p_{jk} is the price that PU j imposes on SU k, and c_j is the cost associated with the channel leased to SU k which must be paid by PU j to regulatory authorities (e.g., FCC). A PU decides to play a game if price p_{jk} is greater than cost c_j of the leased channel (F1.1). The SUs' utility function is defined as

$$U_s = \begin{cases} \log_2 \left(1 + R_{s,k}\right) & \text{Case-I} \\ \log_2 \left(1 + R_{s,k}^{\mathrm{MAX}}\right) & \text{Case-II,} \end{cases} \tag{3}$$

Where $R_{s,k}$ and $R_{s,k}^{\mathrm{MAX}}$ are the transmission rate, as well as its maximum value, of SU k. In Case-I, PU allocates lesser white spaces to SU k than it demands, while in Case-II, PU allocates higher bandwidth to SU k than it demands. The higher the amount of white spaces provided by PU to SU, the higher is the transmission rate of SU k (F2.3). It has been revealed that the number of SUs increases with the price of white spaces that PUs impose to SU.

Yi et al. [10] propose three PU F(1) and two SU F(2) functionalities, namely, determination of the cost of white spaces (F1.1), relay selection (F1.3) and PUs' packet transmission (F1.4), as well as determination of SU's channel access time (F2.2), and SUs' packet transmission (F2.3) in order to increase PUs' monetary gain (A1.1) and to provide dedicated channel access to SUs (A2.1) in centralized (C1.1) SU networks. The purpose is to maximize the PUs' and SUs' network utility functions, U_p and U_s, respectively. The PUs and SUs are rational and selfish in nature. The functionalities are modeled and solved using Stackelberg game, in which the PU is the leader and the SU is the follower in an intra-cooperative (C2.1) mode and inter-cooperative (C3.1) mode, respectively. The Nash equilibrium maximizes both PUs' and SUs' utility functions, U_p and U_s. The PUs' utility function is defined as

$$U_p = u_d + u_r, \tag{4}$$

where u_d and u_r are revenues. Revenue u_d is dependent on the ratio of total PUs' packet transmissions, which include successful packet transmissions through direct transmissions (i.e., from PU host to PU BS) and relaying through SUs to total traffic demand of all PU hosts. Revenue u_r is derived from the white spaces being leased to SUs. The SUs' utility function is defined as

$$U_s = u_s - u_r, \tag{5}$$

where u_s is derived from the total SUs' packet transmissions from all SU hosts. Both U_p and U_s take into account the SNR of the channels. There are two main steps in the Stackelberg game. Firstly, the PU BS (or leader) determines its strategy comprised of a set of potential SU relaying nodes (F1.3) and the costs (i.e,. the price of white spaces per unit access time) to be imposed on SUs (F1.1) and sends the PUs' strategy to SU BS. Using the fixed leader's strategy, the SU BS (or follower) determines the amount of white spaces to request from PUs based on the costs (F2.1); hence, higher cost may reduce the amount of white spaces to request. The SU BS sends the SU strategy to PU BS. Secondly, using a fixed follower's strategy, the PU BS selects relay nodes and finalizes the costs and start packet transmissions (F1.4). Similarly, the SU BS allocates the leased white spaces amongst SUs for their respective packet transmission (F2.3). The spectrum leasing scheme has been shown to increase PUs' and SUs' utility functions, U_p and U_s, as well as to increase the amount of white spaces being leased. This scheme also decreases the price of white spaces per unit access time.

5.1.2. Schemes That Use Nongame Theoretic Approaches. Kim and Shin [26] propose one PU F(1) function, namely, determination of the cost of white spaces (F1.1) in order to increase PUs' monetary gain (A1.1) in distributed (C1.2) SU networks. The purpose is to maximize the PUs' profit by controlling the SUs' admission and eviction strategies. The admission strategy allows the SUs to utilize PUs' channels on the basis of the requested amount of white spaces, which basically yields the PUs' profit. Hence, if SUs demands a small amount of white spaces, then PUs may reject their admissions due to the less monetary gain. This is because the PUs are interested to allocate white spaces to SUs that request larger amount of white spaces in order to maximize their monetary gain, whereas the eviction strategy is set so that SUs evacuate the channel immediately if PUs' activities reappear. The function is modeled and solved using semi-Markov decision process and linear programming in a non-intracooperative (C2.2) mode and non-intercooperative (C3.2) mode, respectively. The PUs allocates their underutilized channels to a group of k SUs. The expected revenue of PUs is defined as

$$r_p = \sum_{k \in K} p_k Q_k K, \tag{6}$$

where p_k is the price that k SUs pay to PU in return of its QoS demand Q_k, while K is the number of SUs in the group. Higher PUs' revenue, which comes with higher price of white spaces (F1.1), indicates higher QoS demand from SUs. It has been shown that PUs' revenue increases with the amount of white spaces. However, the PUs' revenue decreases when the white spaces become oversupplied.

Song and Lin [13] propose one PU F(1) and one SU functionalities, namely, determination of the cost of white spaces (F1.1), as well as SUs' packet transmission (F2.3) in order to increase PUs' monetary gain (A1.1) and to provide dedicated channel access to SUs (A2.1) in distributed (C1.2) SU networks. The purpose is to maximize the profit of PUs while allocating the white spaces to SUs. The function is modeled and solved using auction-based property-rights model mechanism in a nonintracooperative (C2.2) mode and nonintercooperative (C3.2) mode, respectively. In a property-rights model, SUs are divided into non-overlapping groups and a leader is elected from each group. The auction mechanism is divided into time windows, and each window is further divided into two phases, namely, auction and communication. There are *four* main purposes in regard to the auction mechanism. Firstly, it maximizes the overall spectrum utilization. Secondly, it maximizes the number of SU winners (or SU groups that gain a channel). Thirdly, it fulfills the bandwidth requirement of SUs. Note that the channels are heterogeneous and each channel has different amount of bandwidth (or white spaces). Fourthly, it maximizes the PUs' revenue. In a round of bidding, each SU leader determines a bid value based on *hungry degree*, which takes into account the amount of white spaces required by its group of SUs. During the auction phase, the PU auctions off n channels with white spaces to m SU leaders in two phases. Each SU leader uses an auction phase, which is based on its bandwidth requirement, to bid for a leasing channel. Higher value of hungry degree leads to higher bid value. During the first phase of auction, in order to meet the first, second, and third purposes, the PU grants channels to as many groups of SUs as possible to meet their respective minimum requirement on the amount of white spaces. During the second phase of auction, in order to achieve the fourth purpose, the PU allocates the channels with white spaces to SU leaders that offer higher bid values (F1.1). During the communication phase (F2.3), the SUs transmit packets and the PU keeps track of available white spaces for auctions in the next time window. The spectrum leasing scheme has been shown to increase throughput performance in regard to vacant channels.

Wu et al. [7] propose one PU F(1) function, namely, determination of the cost of white spaces (F1.1) in order to increase PUs' monetary gain (A1.1) and to provide dedicated channel access to SUs (A2.1) in centralized (C1.1) SU networks. The purpose is to maximize the PU monetary gain and SUs network utility function U_s, while preventing the collusive SUs to access the PUs' white spaces. The collusive SUs form a coalition and deliberately decrease the price of white spaces offered by PUs. The function is modeled and solved using binary linear programming and convex optimization in an intra-cooperative (C2.1) mode and non-intercooperative (C3.2) mode, respectively. Binary linear programming is a mathematical method to determine the optimal results that comprises binary integers (i.e., 0 and 1). The PU sells white spaces to K SUs with the assistance from a third-party spectrum broker. Upon the reception of bid values $b_k = \{b_1, b_2, \ldots, b_K\}$ from K SU, the spectrum broker announces the winning SUs by defining the channel allocation $x_k = \{x_1, x_2, \ldots, x_K\}$ and the associated price $p = \{p_1, p_2, \ldots, p_K\}$ for K SUs. For the winning SUs, the channel allocation x_k is set to one (i.e., $x_k = 1$), which indicates that the channel has been allocated to winner SU k. The gain of each winning SUs is g_k, which lead to an efficient channel allocation which is used to compute the utility function of SUs; that is, $U_s = \sum_{k=1}^{K} g_k \cdot x_k$. Higher values of U_s indicate higher number of winning SUs in the auction for white spaces. It has been shown that, as the number of winning SUs increases, the price of the white spaces imposed by the PUs as sellers also increases.

5.2. Selecting an Optimal Channel with White Spaces by SUs.

There are six spectrum leasing schemes that focus on motivating the SUs to participate in spectrum leasing by increasing the amount of white spaces for SUs. These schemes have been shown to enhance PUs' or SUs' QoS performance (e.g., throughput).

5.2.1. Schemes That Use Game Theoretic Approaches.

Chan et al. [17] propose two PU F(1) and one SU F(2) functionalities, namely, determination of PUs' and SUs' channel access time (F1.2) and relay selection (F1.3), as well as SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in centralized (C1.1) SU networks. The purpose is to maximize the spectrum utilization of PU and SU networks by adopting the cooperation strategies in between of J PUs and K SUs in the form of PUs and SUs utility functions, U_p and U_s, respectively. In separate cooperation, PU j and SU k form a one-to-one collaborative relationship with each other, while in grand cooperation, PUs and SUs form a coalition that comprises of many one-to-one and one-to-many collaborative relationships with each other. The functionalities are modeled and solved using canonical coalition game theoretic framework and convex optimization problem in a non-intracooperative (C2.2) mode and inter-cooperative (C3.1) mode, respectively. The PU utility function is defined as

$$U_p = u\left(R_p\right) + p_{sp_j} - L\left(c_p\right), \tag{7}$$

where $u(\cdot)$ and $L(\cdot)$ are concave function that maps the PU achievable transmission rate R_p as utility gain and PU cost c_p as utility loss, while p_{sp_j} is the price of white spaces that PU j imposes on SUs. The SU utility function is defined as

$$U_s = r\left(R_s\right) + P_{s_k p}, \tag{8}$$

where $r(\cdot)$ is $(\cdot)$ concave function that projects SU achievable rate R_s as revenue and $P_{s_k p}$ is the price that PUs imposes on SU k in order to lease its channel. It has been shown that the grand cooperation strategy produces higher optimal utility value than individuals' cooperation.

Vazquez-Vilar et al. [20] propose two PU F(1) and one SU F(2) functionalities, namely, relay selection (F1.3), and PUs' packet transmission (F1.4), as well as SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in centralized (C1.1) SU networks. The purpose is to maximize the PUs' and SUs' utility functions U_p and U_s in the presence of a PU communication node pair in order to minimize the SUs' interference to PUs by reducing their power consumption. The PU determines the maximum allowable interference that PU can tolerate from SUs $I^p_{\max}$, while the SUs aim to reduce their transmission power in order to fulfill the requirement $I^p_{\max}$. The function is modeled and solved using Stackelberg game in an intracooperative (C2.1) mode and intercooperative (C3.1) mode, respectively. In this scheme, the PU is the leader and the SU is the follower. To foster collaboration with SUs, the PU maximizes its utility function, and it is defined as

$$U_p = u_p \left(I^s_k, \Delta T^p_p \right), \tag{9}$$

where u_p increases with the increment of interference from SU k (or $I^s_k \leq I^p_{\max}$) and decreases with the increment of PUs' transmission power ΔT^p_p. To foster collaboration with PU, the SU maximizes its utility function, and it is defined as

$$U_s = u_s \left(R^s_k, I^s_k \right), \tag{10}$$

where u_s increases with the increment of the SU transmission rate R^s_K and decreases with interference from SU I^s_k. Note that, $R^s_k(p_k)$ and $I^s_k(p_k)$ increase with the SU transmission power p_k. Maximizing U_s helps to maximize the SU k's power vector $P_K^{I^p_{\max}} = \operatorname{argmax}_p \{ u_s(R^s_k, I^s_k) \}$. This has led to computing the overall utility function of PUs and SUs on the basis of $I^p_{\max}$. The PU selects a SU relay node $k \in K$ (F1.3) that has the lowest transmission power for transmission of PU packets (F1.4), as well as SUs' packets (F2.3) among the other SUs. It has been shown that the proposed scheme achieves higher utility function for both PUs and SUs compared to the traditional scheme.

5.2.2. Schemes That Uses Nongame Theoretic Approaches. Cao et al. [5] propose two PU F(1) and one SU F(2) functionalities, namely, relay selection (F1.3) and PUs' packet transmission (F1.4), as well as SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) in centralized (C1.1) SU networks. The purpose is to maximize the spectrum utilization of PU and SU networks, where the PU and SU BSs operate in an intracooperative (C2.1) mode and intercooperative (C3.1) mode, respectively. The PU source node i selects the best available SU relay node k, and establishes communication with the PU destination node j. The SU relay is used to transmit PU and SU packets using a quadrature modulation scheme, which depends on two factors, namely, power allocation factor $0 \leq F^p_{ij,k} \leq 1$ and weight factor $0 \leq w^p_{ij,k} \leq 1$. The power allocation factor determines the transmission of packets through SU relay node. Note that the SU relay node transmits PU packets only if $F^p_{ij,k} = 1$, the SU packets only if $F^p_{ij,k} = 0$, and both PUs' and SUs' packets if $0 < F^p_{ij,k} < 1$, whereas the weight factor determines the respective throughputs of PU and SU network, respectively. The selected SU relay node k transmits PU and SU packets simultaneously using transmission power $P^s_{ij,k}$ in two orthogonal channels (i.e., in-phase and quadrature channels) exploited using a quadrature modulation approach. The SU relay node relays PU packets using transmission power $F^p_{ij,k} \cdot P^s_{ij,k}$ using in-phase channel and sends SU packets using transmission power $(1 - F^p_{ij,k}) \cdot P^s_{ij,k}$ in quadrature channel. The throughput of PUs and SUs is represented by a weighted sum throughput T_T, which is defined as

$$T_T = \left(1 - w^p_{ij,k} \right) \cdot T_p + w^p_{ij,k} \cdot T_s, \tag{11}$$

where T_p and T_s represent PUs' and SUs' throughput, respectively. Note that $T_T = T_p$ if $w^p_{ij,k} = 0$ and $T_T = T_s$ if $w^p_{ij,k} = 1$, while T_p and T_s achieve a balance if $w^p_{ij,k} = 1/2$. A primal-dual subgradient algorithm, including Lagrange multipliers and the Karush-Kuhn-Tucker conditions, is used to optimize $F^p_{ij,k}$ and $P^s_{ij,k}$ in order to optimize the weighted sum throughput T_T. The PU selects a SU only if it improves throughput performance (F1.3), while the selected SU transmits the PU and SU packets simultaneously (F1.4), or the SU packets only (F2.3) when the PU is inactive. Through achieving balanced throughputs T_p and T_s, the scheme has been shown to maximize T_T, and this is due to the dependence of T_p and T_s on power allocation factor $F^p_{ij,k}$ and weight factor $w^p_{ij,k}$.

Jayaweera et al. [8] propose two PU F(1) and one SU F(2) functionalities, namely, relay selection (F1.3) and PUs' packet transmission (F1.4), as well as SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in centralized (C1.1) and distributed (C1.2) SU networks. The purpose is to maximize the PUs' and SUs' utility functions U_p and U_s, respectively, in terms of power savings of PUs when they collaborate with SUs in the presence of J PUs and K SUs. For centralized CRNs, the functionalities are modeled and solved using reinforcement learning in an intracooperative (C2.1) mode, and intercooperative (C3.1) mode, respectively, whereas for distributed CRNs, the functionalities are modeled and solved using reinforcement learning in a nonintracooperative (C2.2) mode and inter-cooperative (C3.1) mode, respectively. The PU $j \in J$ utility function is defined as

$$U_p = \frac{P_{j,d} - P_j \left(P_{k(j),j} \right)}{P_{j,d}} \left(R_j \left(\alpha_j \right) - R_{j,\min} \right), \tag{12}$$

where $P_{j,d}$ is the maximum transmission power of PU j through direct PU-PU transmission without using a SU relay node, $P_j(P_{k(j),j})$ is the PU j transmission power through PU-SU-PU transmission using SU k as a relay node where $P_{k(j)}$ is the transmission power for SU k to relay the PUs' packets to its destination, and $R_j(\alpha_j)$ and $R_{j,\min}$ are the achievable transmission rate of PU j after allocating α_j of white spaces to SUs and the minimum transmission rate of PU j for direct transmission, respectively. The SU $k \in K$ utility function is defined as

$$U_{s,k} = \alpha_j W_j \log \left(1 + \mathrm{SNR}_{k,i} \right) \left(\mathrm{BER}_{kj,\min} - \mathrm{BER}_{kj,(P_{k(j)})} \right), \tag{13}$$

where W_j is the bandwidth used by SU to transmit its own signal, $\mathrm{SNR}_{k,i}$ is the signal-to-noise ratio of SU k, while $\mathrm{BER}_{kj,\min}$ and $\mathrm{BER}_{kj,(P_{k(j)})}$ are the minimum and observed Bit Error Rate (BER) values of SU k while relaying PU j's packets. It has been shown that the transmission power of PU decreases with increasing the transmission power of SU.

Murawski and Ekici [27] propose two PU F(1) and one SU F(2) functionalities, namely, relay selection (F1.3) and PUs' packet transmission (F1.4), as well as SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in distributed (C1.2) SU networks. The purpose is to maximize the throughput of PUs and SUs in an intra-cooperative (C2.1) mode and inter-cooperative (C3.1) mode, respectively. The network considers a single PU source node that communicates with a PU destination node through direct PU-PU transmission or indirect PU-SU-PU transmission via SU relay node. The PU destination node transmits Request to Send (RTS), while the SU replies with Request to Cooperate (RTC) composed of channel state information upon receiving RTS from the PU. Subsequently, the PU destination node selects the suitable SUs as relay nodes using the channel state information. The criterion adopted by PU for selecting a suitable SU relaying node is based on the basis of higher throughput value of a given PU-SU-PU link with respect to the throughput value of PU-PU direct link. The PU destination node sends clear to coordinate (CTC) message to a selected SU relay node, which indicates that a given PU-SU-PU link offers higher throughput than the PU-PU direct link; whereas, if the throughput being offered by the PU-SU-PU link is lower than the PU-PU direct link, then the PU destination node sends clear to send (CTS) message to the SU relay node, which indicates that the direct link of PU-PU communication can take place. For the calculation of expected throughput value either from PU-SU-PU link or from PU-PU direct link, abackoff mechanism of distributed coordination function [38] is used. The expected throughput value is dependent on the probability of successful packet transmission P_s, packet transmission time t_{packet}, collision detection time t_{collide}, and the expected size of PU packets $E_{\text{packet size}}$. Furthermore, for attaining a higher throughput gain, adaptive modulation schemes (e.g., BPSK, QPSK, and 16-QAM) is used with respect to the SNR of the channels. It has been shown that, higher throughput can be achieved by changing the adaptive modulation scheme from BPSK to QPSK, and from QPSK to 16-QAM. Additionally, higher throughput of PUs can be achieved by reducing the number of SUs as relaying nodes which reduces the communication overheads.

Toroujeni et al. [28] propose two PU F(1) and one SU F(2) functionalities, namely, relay selection (F1.3) and PUs' packet, transmission (F1.4), as well as SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in distributed (C1.2) SU networks. The purpose is to increase the link reliability by maximizing the transmission rate of a PU communication node pair and K SUs. The functionalities are modeled and solved using Orthogonal Frequency Division Multiplexing (OFDM) [39] symbols in an intra-cooperative (C2.1) mode and inter-cooperative (C3.1) mode, respectively. There are a total of $N_s + N_{pp}$ OFDM symbols, in which N_{pp} symbols are dedicated for a PU-PU communication node pair for direct transmission, and the N_s symbols are dedicated for PU-SU and SU-SU transmissions, respectively. The PU selects the maximum transmission link R_p either from PU-PU direct link R_{pp} or from PU-SU-PU relayed link R_{psp}, and it is defined as

$$R_p = \max\left\{R_{pp}, R_{psp}\right\}. \tag{14}$$

Each SU $k \in K$ chooses the best channel to relay the packets from PU source node to PU destination node as well as its own packets to another SU. The SU cooperates with PU if SU-SU transmission rate R_{ss} is equal to the price p_k, which is charged by the PU, times the SU-PU transmission rate R_{sp}, and it is defined as

$$R_{ss} = \sum_{k=1}^{K} p_k \cdot R_{sp}. \tag{15}$$

Higher value of R_{ss} indicates higher achievable transmission rate between SU relay node and PU destination node. It has been shown that as the distance increases between PU source node and SUs, it decreases the number of selected SUs as relaying nodes. Furthermore, higher cost being incurred by SUs reduces the achievable transmission rates of PUs although it increases the achievable transmission rates of SUs.

5.3. Scheduling the Channel Access of PUs and SUs.

There are ten spectrum leasing schemes that focus on scheduling of channel access time in between of PUs and SUs for their respective transmission. These schemes have been shown to enhance PUs' and SUs' QoS performance (e.g., throughput).

5.3.1. Schemes That Use Game Theoretic Approaches.

Chen et al. [29] propose two PU F(1) and one SU F(2) functionalities, namely, determination of PUs' and SUs' channel access time (F1.2) and relay selection (F1.3), as well as SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in distributed (C1.2) SU networks. The purpose is to maximize the PUs' and SUs' network utility functions U_p and U_s in the presence of J PUs and K SUs. The functionalities are modeled and solved using a three-tier game in a non-intracooperative (C2.2) mode and nonintercooperative (C3.2) mode, respectively. The PU and SU network communicate with each other using a control channel protocol in order to participate and achieve a game equilibrium. Both PUs and SUs are rational in nature. The PU selects the suitable SUs as relay nodes to transmit PU's packets in order to increase its transmission rate and the SUs in return achieve a portion of channel access time set by the PU to maximize their transmission rate. The PU divides the transmission period into three phases. The first phase is for primary transmission (PU-PU and PU-SU) during which the PUs transmit their packets to other PUs and SUs. The second phase is for relayed transmission (SU-PU) during which the SUs help the PUs to relay PUs' packets, whereas the third phase is for secondary transmission (SU-SU) during which the SUs transmit their own packets. The length of the primary transmission phase is α, the relay nodes transmission phase is $(1-\alpha)(1-\beta)$, and the secondary transmission phase is $(1-\alpha)\beta$. Higher value of α indicates that PUs is willing to lease its spectrum to SUs while higher value of β encourages SUs to collaborate and relay PUs' packets. Thus, the PU must determine optimal values of α and β (F1.2) that maximize its own and SUs' transmission rate. The PU j utility function is defined as

$$U_{p,j} = \min\left\{\alpha R_{ps,k}, (1-\alpha)(1-\beta) R_{sp,k}\right\}, \qquad (16)$$

where R_{ps} and R_{sp} are the maximum transmission rate through SU relay nodes (F1.3). The SU k utility function is defined as

$$U_s = \beta R_{ss} - (1-\alpha) p_s P_s, \qquad (17)$$

where p_s is the cost of per unit power P_s consumed by SU k as relay node to transmit PU source node packet to PU destination node. Therefore, the utility function of SU k is the difference between its revenue in terms of achievable rate R_{ss} (F2.3) and the cost of power which SU k must bear in order to relay the PU's packets. It has been shown that as the distance increase between the PU and SUs, their utility functions increase until a certain limit which then decrease.

Huang et al. [18] propose three PU F(1) and one SU F(2) functionalities, namely, determination of the cost of white spaces (F1.1), determination of PUs' and SUs' channel access time (F1.2), and relay selection (F1.3), as well as SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in centralized (C1.1) SU networks. The purpose is to maximize the PUs' and SUs' utility functions U_p and U_s in the presence of J PUs and K SUs. The functionalities are modeled and solved using canonical coalition game in an intracooperative (C2.1) mode and intercooperative (C3.1) mode, respectively. The PU divides a unit time slot into three subslots for primary transmission (PU-PU and PU-SU), relayed transmission (SU-PU), and secondary transmission (SU-SU), respectively. The length of the primary transmission subslot is $1-\alpha$, the relay nodes transmission subslot is β, and the secondary transmission subslot is $\alpha-\beta$. Higher value of α indicates that PUs are willing to lease their spectrum to SUs while higher value of β encourages SUs to collaborate more and relay PU packets. Thus, the PU must determine the optimal values of α and β that maximize its own as well as SUs' transmission rate. The PU $j \in J$ utility function is $U_p = F(R_p)$, where $F(\cdot)$ is an increasing concave function that represents PUs' gain and R_p is the minimum achievable transmission rate, which can be either from PU-SU or from SU-PU, and dependent on transmitter power P_t, channel gain G, and noise level σ^2. The SUs' utility function is $U_s = G(R_s) - p_s$, where $G(\cdot)$ is an increasing concave function that represents SUs' gain and p_s is the price that SU needs to pay in order to lease channels from PUs. It has been shown that as the SUs' channel access time increases, the transmission rate of SUs increases significantly, which increases the PUs monetary gain while decreasing its transmission rate since SU uses more power to transmits its own packets.

Wang et al. [30] propose three PU F(1) and two SU F(2) functionalities, namely, determination of the cost of white spaces (F1.1), determination of PUs' and SUs' channel access time (F1.2), and relay selection (F1.3), as well as determination of SU's channel access time (F2.2) and SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in centralized (C1.1) SU networks. The purpose is to maximize the PUs' and SUs' utility functions U_p and U_s, respectively, in the presence of a PU communication node pair and K SUs. The functionalities are modeled and solved using Stackelberg game in an intra-cooperative (C2.1) mode and inter-cooperative (C3.1) mode, respectively. The PU divides the transmission period into three phases. The first phase is for primary transmission (PU-PU and PU-SU) during which the PUs transmit their packets to other PUs and SUs. The second phase is for relayed transmission (SU-PU) during which the SUs help the PUs to relay PUs' packets whereas the third phase is for secondary transmission (SU-SU) during which the SUs transmit their own packets. The length of the primary transmission phase is $(T-t_s)/2$, the relay nodes transmission phase is $(T-t_s)/2$, and the secondary transmission phase is t_s. The PU utility function is defined as

$$U_p = G_{\mathrm{SNR}}\left(\mathrm{SNR}_{pp} + \mathrm{SNR}_{psp}\right)\frac{T-t_s}{2T}, \qquad (18)$$

where G_{SNR} is the channel gain per unit SNR and SNR_{pp} and SNR_{psp} are the SNR values of PU-PU direct link and PU-SU-PU relayed link whereas, the SUs' utility function is defined as

$$U_s = G_{t_s} - c\frac{T-t_s}{2}\left\{\frac{\left(\mathrm{SNR}_{ps}+1\right) p\cdot t_s\cdot\sigma^2}{\left(\mathrm{SNR}_{ps} - pt_s\right) G_{pp}}\right\}, \qquad (19)$$

where c is the cost per unit energy consumption, p is the price that SUs needs to bear in order to buy white spaces from PUs, and σ^2 is the noise variance. It has been shown that as the distance increase between the PU and SUs, their utility functions increase until a certain limit which then decrease.

Stanojev et al. [31] propose two PU F(1) and one SU F(2) functionalities, namely, determination of PUs' and SUs' channel access time (F1.2) and relay selection (F1.3), as well as SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in distributed (C1.2) SU networks. The purpose is to maximize the PUs' transmission rate and the SUs' utility function. The PU divides a unit time slot into three subslots for primary transmission (PU-PU and PU-SU), relayed transmission (SU-PU), and secondary transmission (SU-SU), respectively. The length of the primary transmission subslot is $(1-\alpha)\cdot t_{\mathrm{slot}}$, the relay nodes transmission subslot is $\alpha\cdot\beta\cdot t_{\mathrm{slot}}$, and the secondary transmission subslot is $\alpha\cdot(1-\beta)\cdot t_{\mathrm{slot}}$. Higher value of α and lower value of β encourage SUs to collaborate, and so the PU must determine optimal values of α and β, while maximizing its own transmission rate. The functionalities are modeled and solved using Stackelberg game in a nonintracooperative (C2.2) mode and intercooperative (C3.1) mode, respectively. In this scheme, PU is the leader and SU is the follower. The game aims to foster collaboration between PUs and SUs by maximizing the PUs' transmission rate and enhancing the SUs' utility function. The PU source node i chooses a set of SU relay node k that provides an optimum value of PU transmission rate, which is dependent on the transmission rate from PU source node i to SU relaying node k, or $R_{ij,k}^{ps}$, while SU relaying node k calculates the transmission rate from SU relay node k to PU destination node j, or $R_{ij,k}^{sp}$, as well as β. Hence, the value of β must be chosen carefully to encourage collaboration between PU and SU. The choice of β must maximize the SU-PU transmission rate $(\alpha \cdot \beta \cdot t_{\text{slot}}) \cdot R_{ij,k}^{sp}$, on the other hand, the choice of α must maximize the SU-SU transmission rate $\{(\alpha \cdot (1-\beta)) \cdot t_{\text{slot}}\} \cdot R_k^{ss}$. The optimal value of β is $\widehat{\beta} = \operatorname{argmax}_{\beta \in [0,1]} \beta \cdot R_{ij,k}^{sp}$ and $\widehat{\beta}$ is applied in the calculation of $\widehat{\alpha} = f(1/\widehat{\beta})$. The PU source node selects a suitable SU relay node (F1.3) to transfer its packets to PU destination node (F1.4) if SU relay node provides higher transmission rate; otherwise, it chooses PU-PU direct link. The PU calculates channel access time for PUs and SUs (F1.2). It has been shown that, as the number of SU relay nodes increases, the outage probability of PU decreases and the transmission rate of SUs increases. The SUs aim to maximize their utility function in order to transmit its own packets (F2.3). The SUs utility function is $u_{P_k, P_{-k}}^{ss}$, where P_k is the transmission power of SU relaying node k, and P_{-k} is a vector of the transmission power of the SU nonrelaying nodes. The PU adjusts $\widehat{\beta}$ to determine the time distribution among PUs' and SUs' (F1.2) transmissions, and this is followed by the selection of the best available SUs as relay nodes (F1.3) for possible communication between a PU node pair. It has been shown that the PUs' and SUs' throughput performances can be increased by increasing the number of SU relay nodes k and decreasing the distance between PU and SU.

Wang et al. [32] propose two PU F(1) and one SU F(2) functionalities, namely, determination of PUs' and SUs' channel access time (F1.2) and relay selection (F1.3), as well as SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in distributed (C1.2) SU networks. The purpose is to maximize the PUs' and SUs' utility functions U_p and U_s in the presence of a PU communication node pair and K SUs. The functionalities are modeled and solved using the game theoretic approach and the Stackelberg equilibrium in a nonintracooperative (C2.2) mode and nonintercooperative (C3.2) mode, respectively. In this game theoretic approach, PUs and SUs are rational in nature, in which the PUs and SUs attempt to achieve their respective equilibrium point. The PU selects suitable SUs that transmit PU packets as relay using their respective transmission power, while the SUs in return achieve a portion of channel access time set by the PU to transmit their own packets. The PU divides a unit time slot into two sub-slots for primary transmission (PU-PU, PU-SU, and SU-PU) and secondary transmission (SU-SU), respectively. The length of the primary transmission subslot is α, while the secondary transmission subslot is $1-\alpha$. Higher value of α indicates that PUs are willing to lease its spectrum to SUs in order to maximize its packet transmission while allocating the remaining time to SUs for their own packet transmission. Thus, PU must determine the optimal value of α (F1.2) that maximize its own and SUs' transmission rate. The PU utility function is defined as

$$U_p = \alpha R_p(\alpha), \tag{20}$$

where $R_p(\alpha)$ is the achievable transmission rate through SU relay nodes (F1.3) and it is dependent on transmitter power P_t, channel gain G, and noise variance σ^2. The SUs' utility function is defined as

$$U_s = r_k(R_k)\,t_k - \frac{1}{2}\alpha P_k, \tag{21}$$

where r_k, R_k, and t_k are the revenue, achievable transmission rate, and allocation time of SU k, and P_k is the transmission power used by SU k to relay the PUs' packets to PU destination and therefore it is considered as a cost by SU k. Therefore, the utility function of SU k is the difference between its revenue in terms of achievable transmission rate (F2.3) and the energy cost that SU k must bear to relay the PUs' packets. It has been shown that PUs' utility function increases with the increment of the α value. Furthermore, as the distance between PUs and SUs decreases, it increases their utility functions significantly because of higher channel gain.

Zhang et al. [33] propose two PU F(1) and one SU F(2) functionalities, namely, determination of PUs' and SUs' channel access time (F1.2), relay selection (F1.3), and SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in distributed (C1.2) SU networks. The purpose is to maximize the PUs' and SUs' utility functions U_p and U_s in order to enhance their transmission rate in the presence of a PU communication node pair and K SUs. The functionalities are modeled and solved using game theory and the Nash equilibrium in a non-intracooperative (C2.2) mode and inter-cooperative (C3.1) mode, respectively. In this game, the PU selects the suitable SUs as relay nodes to transmit PUs' packets using their respective transmission power and in return, the SUs receive a portion of channel access time set by the PU to transmit their own packets. The PU divides a unit time slot into three subslots for primary transmission (PU-PU and PU-SU), relayed transmission (SU-PU), and secondary transmission (SU-SU), respectively. The length of the primary transmission subslot is $1-\alpha$, the relay nodes transmission subslot is $\alpha\beta$, and the secondary transmission subslot is $\alpha(1-\beta)$. Higher value of α indicates that PUs are willing to lease its white spaces to SUs while higher value of β encourages SUs to collaborate more and relay PU packets. Thus, the PU must determine optimal values of α and β (F1.2) that maximize its own and SUs' transmission rate. The PUs' utility function is defined as

$$U_p = R_{psp} - R_{pp} + \alpha c_p P_p, \tag{22}$$

where R_{psp} and R_{pp} are the achievable transmission rate through SU relay nodes (F1.3) and PU-PU direct transmission. These rates are dependent on transmission power P channel gain G and noise power N whereas c_p is the cost per unit of transmission power consumed by PU source node to transmit its packets to SUs and PU destination node. The SUs' utility function is defined as

$$U_s = \alpha(1-\beta)\log_2\left(1+\frac{P_s G_s}{N}\right) - \alpha c_s P_s, \tag{23}$$

where c_s is the cost per unit transmission power consumed by SU relay node k to transmit PU source node's packets to PU destination node. Therefore, the utility function of SU k is the difference between its revenue in terms of the achievable rate (F2.3) and the energy cost that SU k must bear to relay the PUs' packets. It has been shown that, as the distance increases between the PU and SUs, their utility function increases until a certain limit which then decreases.

Zhu et al. [34] propose two SU F(2) functions, namely, collaborative selection (F2.1) and determination of SU's channel access time (F2.2) in order to provide dedicated channel access to SUs (A2.1) in distributed (C1.2) SU networks. There are two types of markets, namely, primary market (comprised of SU service providers and PUs) and secondary market (comprised of SU service providers and SU hosts). The functionalities are modeled and solved using a hierarchical game theoretic framework comprised of upper- and lower-level games and in a non-intracooperative (C2.2) mode and non-intercooperative (C3.2) mode, respectively. The purpose is to maximize the SUs' service provider and SU network utility functions, $U_{p,i}(t)$ and $U_{s,i}(t)$, respectively. The hierarchical game theoretic framework is as follows.

(i) Secondary market allows SU hosts to purchase white spaces from SU service providers on a short-term basis (e.g., minutes), and it is a lower-level game modeled by evolutionary game. Each SU service provider i offers white spaces, which are represented by bandwidth b_i and price p_i. Note that higher price p_i for a particular bandwidth b_i reduces demand levels, and so it improves network performance. Subsequently, each SU host competes and selects a SU service provider. Hence, the secondary market implements collaborator selection (F2.1). Each SU aims to maximize its individual utility function defined as

$$U_{s,i}(t) = \alpha \cdot \frac{b_i(t)}{p_i}, \tag{24}$$

where α is a constant based on network performance requirement, in order to maximize its network performance satisfaction. The number of SUs that choose service provider i is represented by $n_i(t)$.

(ii) Primary market allows SU service providers to purchase white spaces from PUs (or spectrum brokers) on a long-term basis (e.g., weeks or months), and it is a upper-level game modeled by differential game. Each SU service provider i purchases some amount of white spaces $c_i(t)$ from PUs based on the selection of SU service providers $x_i(t)$ in order to maximize profits. Hence, it implements the determination of SU's channel access time (F2.2). Note that higher amount of the purchased white spaces improves network performance and so it attracts more SUs; however, it reduces monetary revenues. Each SU service provider i adjusts the amount of white spaces $c_i(t)$, and maximizes its profit defined as

$$U_{p,i}(t) = p_i \cdot n_i(t) - \beta_i \cdot c_i^2(t), \tag{25}$$

where $p_i \cdot n_i(t)$ represents the monetary revenue, $\beta_i \cdot c_i^2(t)$ represents the cost paid to the PUs, and β_i is a constant weight. Note that, with $c_i^2(t)$, it causes the cost to increase rapidly, and so it prevents a SU service provider i from being too aggressive. At Nash equilibrium, each SU service provider obtains maximized profit. In differential game, the SU service providers make decision simultaneously; however, some providers may make decision first, and they are called the leaders. In this case, a Stackelberg differential game can be applied to achieve Stackelberg equilibrium. In Stackelberg game, the leader providers make decisions first, followed by follower providers. So, the leader providers can achieve higher pay-off, and the follower providers make decision based on the optimal strategies made by the leader providers. The spectrum leasing scheme has been shown to increase SU service providers' profits.

5.3.2. Schemes That Uses Nongame Theoretic Approaches. Asaduzzaman et al. [35] propose three PU F(1) and one SU F(2) functionalities, namely, determination of PUs' and SUs' channel access time (F1.2), relay selection (F1.3), and PUs' packet transmission (F1.4), as well as determination of SU's channel access time (F2.2) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in centralized (C1.1) SU networks. The purpose is to minimize the outage probability of PUs' network and to maximize the outage capacity of SUs' network. The outage probability indicates the halt of PUs' packet transmission for a certain period of time when the transmission signal power is less than a certain threshold value while the outage capacity is the SUs' transmission rate during outage. Hence, generally speaking, the functionalities are based on transmission rate and channel access duration of PUs and SUs in an intra-cooperative (C2.1) mode and inter-cooperative (C3.1) mode, respectively. The network considers a PU communication node pair, and it is separated by a single centralized SU network comprised of potential SU relaying nodes K. The PU source node i selects the best available SU relaying node $k \in K$ and creates a multiple-hop communication with the PU destination node j. The PU source node makes decision whether to communicate directly or through SU relaying nodes to the PU destination node. The selection of SU relaying node k is based on the transmission rate offered by itself in a PU-SU-PU communication, $R_{ij,k}^{psp}$. The $R_{ij,k}^{psp}$ is computed separately in two steps. Specifically, PU source node i calculates the transmission rate from PU source node i to SU relaying node k, or $R_{ij,k}^{ps}$ and SU relaying node k calculates the transmission rate from SU relaying node k to PU destination node j, or $R_{ij,k}^{sp}$. Subsequently, the PU source node i selects the best available SU relaying node $k \in K$ based on the transmission rate of the bottleneck link or $R_{ij,k}^{psp} = \min\{R_{ij,k}^{ps}, R_{ij,k}^{sp}\}$. The PU source node i communicates through SU relaying node k when $R_{ij,k}^{psp} > R_{ij}^{pp}$; otherwise, the PU source node i chooses to communicate directly with PU destination node, where R_{ij}^{pp} represents the transmission rate of PU-PU direct transmission. Note that the transmission rates $R_{ij,k}^{psp}$ and R_{ij}^{pp} are dependent on SNR. The PU divides the transmission period into three phases. The first phase is for primary transmission (PU-PU and PU-SU) during which the PUs transmit their packets to other PUs and SUs. The second phase is for relayed transmission (SU-PU) during which the SUs help the PUs to relay PUs' packets, whereas the third phase is for secondary transmission (SU-SU) during which the SUs transmit their own packets. The first two phases, namely, A and B, are allocated to the transmission of PU packets, specifically PU-SU and SU-PU, respectively, while the third phase C is for SU-SU transmission. Hence, the outage capacity of SU is dependent on the time duration of phase C and the transmission rate of SU-SU. Denote the requirement on PU's transmission rate by R_{ij}; the outage of PU occurs whenever $R_{ij,k}^{psp} < R_{ij}$ and $R_{ij}^{pp} < R_{ij}$. The PU source node selects a suitable SU relay node (F1.3) to transfer its packets to PU destination node (F1.4) if SU relaying node provides higher transmission rate; otherwise, it chooses PU-PU direct link. The PU calculates channel access time for PUs (F1.2) and SUs (F2.2). It has been shown that as the number of SU relaying nodes increases, the outage probability of PU decreases and the transmission rate of SUs increases.

Khalil et al. [36] propose three PU F(1) and one SU F(2) functionalities, namely, determination of PUs' and SUs' channel access time (F1.2), relay selection (F1.3), and PUs' packet transmission (F1.4), as well as SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in centralized (C1.1) SU networks. The purpose is to maximize the PUs' and SUs' utility functions U_p and U_s, respectively. The functionalities are modeled and solved using Lyapunov Optimization [40] in a non-intracooperative (C2.2) mode and inter-cooperative (C3.1) mode, respectively. The PU divides a unit time slot into three sub-slots for primary transmission (PU-PU and PU-SU), relayed transmission (SU-PU), and secondary transmission (SU-SU), respectively. The length of the primary transmission sub-slot is $1-\alpha$, the relay nodes transmission sub-slot is $\alpha\beta$, and the secondary transmission sub-slot is $\alpha(1-\beta)$. The main objective of the PU j's utility function is to improve its transmission rate, and it can be computed with and without the cooperation from SUs as relay nodes as follows:

$$U_p = \begin{cases} R_{p,j}, & \text{PU-PU transmission} \\ (1-\alpha)\cdot R_{p,jk}, & \text{PU-SU-PU transmission,} \end{cases} \tag{26}$$

where $R_{p,j}$ represents the PUs' achievable direct transmission rate without any cooperation with SUs and $R_{p,jk}$ represents the achievable PUs' transmission rate in cooperation with SUs as relaying nodes. Higher $U_p = R_{p,j}$ is applied when PUs' direct transmission rate is greater than the PUs' transmission rate in cooperation with SUs; otherwise, $U_p = (1-\alpha)R_{p,jk}$ is applied. The PU cooperates with SU when transmission rate is at least equal to its minimum transmission rate $R_{p,j}$ (or $R_{p,j} \le R_{p,jk}$). The main objective of SU k's utility function is to improve its own transmission rate which is defined as

$$U_s = \alpha\left(1-\beta\right)R_{s,k}, \tag{27}$$

where $R_{s,k}$ represents the transmission rate of SU k. Higher U_s indicates that the transmission rate of SU k increases due to the higher amount of channel access time being allocated for its own transmission. It has been shown that, the proposed scheme achieves higher transmission rate due to the cooperation between PUs and SUs.

Zhou et al. [11] propose one PU F(1) and two SU F(2) functionalities, namely, determination of the cost of white spaces (F1.1), as well as determination of SU's channel access time (F2.2) and SUs' packet transmission (F2.3) in order to increase PUs' monetary gain (A1.1) and to provide dedicated channel access to SUs (A2.1) in distributed (C1.2) SU networks. The purpose is to enable the SUs to acquire the white spaces efficiently when PUs intends to lease it in order to maximize the monetary gain of PU and transmission rate SU networks. The functionalities are modeled and solved by introducing rules for spectrum management and spectrum leasing in an intra-cooperative (C2.1) mode and inter-cooperative (C3.1) mode, respectively. The spectrum management rule is set by the PU BS to regulate the spectrum leasing process in order to maximize PUs' revenue F(1.1) and guarantee a fair spectrum trade market by offering the discounted spectrum price to SUs in combination with spectrum and time optimization. The spectrum leasing rule is set by the SUs, through which SUs takes the decision to acquire the white spaces from PUs if it fulfills the bandwidth requirements desired by SUs for a specified period of time (F2.2), which SUs mentioned to PU BS for its packet transmission (F2.3). It has been shown that as PU allocates more channel bandwidth to SUs while increasing the number of transmission slots, it maximizes the SUs transmission rate and throughput.

5.4. Continuous Monitoring of White Spaces Being Leased to SUs by PUs. There are four spectrum leasing schemes that focus on the monitoring of SUs' channel access activities in spectrum leasing by PUs', so that SUs are ensued to follow (or fulfill) suit according to spectrum leasing contract with PUs. These schemes have been shown to enhance PUs' or SUs' QoS performance (e.g., throughput).

5.4.1. Schemes That Use Game Theoretic Approaches. Jayaweera et al. [6] propose one PU F(1) and one SU F(2) functionalities, namely, relay selection (F1.3) and SUs' packet transmission (F2.3) in order to enhance the network performance of PUs (A1.2) and to provide dedicated channel access to SUs (A2.1) in centralized (C1.1) SU networks. The purpose is to maximize the PUs' and SUs' utility functions, U_p and U_s, respectively. Both PUs and SUs are rational and selfish in nature. The functionalities are modeled and solved using a game theoretic framework in a nonintracooperative (C2.2) mode and nonintercooperative (C3.2) mode, respectively. The Nash equilibrium maximizes both PUs' and SUs' utility functions, U_p and U_s. Each PU actively adjusts an interference cap I_C, which is the maximum level of interference from SUs I_{SU}. The PU selects those SUs (F1.3) that do not violate the interference cap I_C, so that PU achieves its minimal SNR and QoS level. The PUs' utility function is defined as

$$U_p = \left(I_{c,\max} - \left(I_c - I_{\mathrm{SU}}\right)\right) I_c. \tag{28}$$

The PU constantly broadcasts the I_c and I_{SU} to all SUs whereas each SU adjusts its transmission power to ensure that the current level of interference from SUs I_{SU} is lower than I_c, in order to maximize its own rewards in terms of higher throughput for packet transmission (F2.3). The SU utility function is defined as

$$U_s = \left(I_c - \lambda_s I_{\mathrm{SU}}\right) r_s, \tag{29}$$

where λ_s and r_s are positive coefficient and reward function, respectively. The spectrum leasing scheme has been shown to increase PUs' and SUs' utility functions U_p and U_s, as well as to increase the rewards (i.e., transmission rate per user). Similar schemes have also been applied in [19, 37] as follows.

(i) In [19], the purpose is to examine the power control mechanism and its effect on the utility function of PUs. The PUs' utility function, which aims to achieve the required QoS performance of PUs and SUs, is defined as:

$$U_p = I_c - \left(I_c - I_{\mathrm{SU}}\right)^2 - \left(e^{(I_{\mathrm{SU}} - I_c)} - 1\right). \tag{30}$$

Whereas, the SU utility function, which aims to achieve SUs' energy efficiency, is defined as

$$U_s = \frac{R_{s,k}\left(1 - e^{[0.5(\mathrm{SNR}_s)]}\right)}{p_k}, \tag{31}$$

where $R_{s,k}$ and p_k are the transmission rate and transmission power of SU k. The SUs' utility function defines SUs' packet transmission (F2.3), which represents the number of successful transmitted bits per unit of transmission power.

(ii) In [37], the propose is to adjust the PUs' interference level in accordance with the SUs' transmission requirements of SNR and QoS levels, so that PUs and SUs maximize their respective utility functions. The PUs' utility function is defined as

$$U_p = \left\{\left(I_{c,\max} - \left(I_c - I_{\mathrm{SU}}\right)\right) I_c\right\} \cdot r_p, \tag{32}$$

where r_p is a continuous reward function that defines the PUs' gain while leasing its spectrum to SUs. The SUs' utility function is defined as

$$U_s = \frac{r_s}{1 + e^{\lambda(I_{\mathrm{SU}} - I_c)}}, \tag{33}$$

where r_S is the reward function of SUs, which depends on the transmitting power of SU $k \in K$.

5.4.2. Scheme That Uses Nongame Theoretic Approaches. Sodagari et al. [15] propose one PU F(1) and one SU F(2) functionalities, namely, determination of the cost of white spaces (F1.1), as well as determination of SU's channel access time (F2.2) in order to increase PUs' monetary gain (A1.1) and to provide dedicated channel access to SUs (A2.1) in distributed (C1.2) SU networks. Generally speaking, SUs send private information to PUs regarding their channel access time (i.e., arrival and departure times) and bid values during the auction process in which the PUs provide suitable channel allocations to SUs. There are two types of SUs, namely, truthful SUs and collusive SUs. Truthful SUs provide the private information to PUs while the collusive SUs collaborate among themselves through sharing the private information and subsequently misreport the information in order to gain the channel access. There are two approaches to misreport the information. Firstly, the collusive SUs share the bid values so that the SUs either set the bid value to the lowest or slightly higher values. Secondly, the collusive SUs share the arrival time so that the SUs either set to the arrival time to the latest or slightly earlier values, and this minimizes the competitiveness among the SUs for channel access in auctions and subsequently minimizes the bid values. The functionalities are modeled and solved using an approach called Dominant Strategy Incentive Compatible (DSIC) in which a SU can reduce its payment to the PUs in an auction process without collusion, in an intracooperative (C2.1) mode and nonintercooperative (C3.2) mode, respectively. Specifically, with respect to SU k, denote the bid value by $b_k(\pi_k)$ and the price p_{jk} set by the PU and j the SU adopts a π_k policy to determine its bid value that maximizes gain $b_k(\pi_k) - p_{jk}$ such that if SU k colludes with other SUs, it fails to minimize the gain. The π_k policy is the decision policy which PUs define for the allocation of white spaces to a truthful SU k in the presence of SUs as bidders. It has been shown that truthful SUs receive higher gain and higher occurrence of winning bids for channel access compared to collusive SUs while the PUs monetary gain decreases.

6. Performance Enhancement of Spectrum Leasing Schemes

Table 2 presents the performance enhancement achieved by the spectrum leasing schemes compared to conventional and traditional approaches in CRNs. The performance metrics are as follows.

(P1) *Lower Outage Probability*. Lower outage probability indicates lesser interruptions of packet transmissions in which transmission does not take place for a certain period of time. For instance, the interruption may be caused by transmission power which is less than a certain threshold value [41], as well as lack of white spaces [42]. Lower outage probability has been shown to enhance QoS (P3) [32].

(P2) *Higher Outage Capacity*. Outage capacity is the maximum achievable transmission rate during any instances of outage. Higher outage capacity indicates higher achievable transmission rate in the presence of outages from time to time, and so it also indicates lower occurrence of outages [41]. Higher outage capacity has been shown to enhance QoS (P3) [35].

(P3) *Better QoS Level*. Through spectrum leasing, the PUs and SUs achieve QoS enhancement. For instance, higher throughput indicates higher rate of successful data transmission over a channel, which provides better QoS [5]. Higher throughput may also indicate more white spaces, in terms of time duration, being offered to SUs by PUs at a specified cost [16].

(P4) *Higher Energy Efficiency Indicates Lower Energy Consumption by PUs* [8]. This is because the SUs help the PUs to relay their packets due to the low channel quality in PUs' direct transmission to PU destination node [37]. With reduced unsuccessful transmission attempts by PUs, the PUs consume lower transmission power and there are more white spaces available to be leased to SUs for monetary gain (P5).

(P5) *Higher Monetary Gain*, *Which is the Gain Exclusive for PUs A(1.1)*. The PUs receive monetary gain as revenue based on the price of the white spaces being offered to SUs through spectrum leasing [10].

(P6) *Balanced Trade-off between Cost of White Spaces and Monetary Gain*. Generally speaking, the cost of white spaces paid by the SUs is set by the PUs. Higher cost provides higher monetary gain received by PUs at the expense of SUs. Hence, a balanced trade-off between the cost of white spaces and monetary gain provides a win-win solution for both PUs and SUs [16].

(P7) *Balanced Trade-off between PUs' and SUs' Channel Access Time*. Generally speaking, higher channel access time among the PUs may provide better QoS level (P3) among the PUs at the expense of reduced channel access time among SUs and vice versa [35]. Hence, a balanced trade-off between PUs' and SUs' channel access times provides a win-win solution for both PUs and SUs.

(P8) *Better Security Level*. Through the detection of malicious SUs that access PUs' channels in an illegitimate manner, better security level can be achieved contributing to better QoS level (P3) (e.g., throughput) and monetary gain (P5). For instance, in [15], the SUs report their respective channel access time, which is closely monitored by PUs. Hence, malicious SUs that mislead PUs with incorrect information (e.g., channel access time) in order to compete for channel access can be detected by PUs. Subsequently, the PUs evict the malicious SUs from their channels, and this has been shown to achieve higher throughput for PUs and SUs, as well as an increase in PUs' monetary gain.

(P9) *Lower PUs' Interference Level*. Lower interference level to PUs in the use of white spaces by SUs provides better QoS (P3) to PUs. For instance, in [6], a PUs' interference cap, which is the maximum interference level that PUs can tolerate in the use of white spaces by SUs, is set in order to increase PUs' and SUs' throughput performance.

7. Open Issues

This section discusses important open issues that can be pursued in this research area.

7.1. Enhancing Auction and Coordination Mechanisms.

Generally speaking, auction enhances the performance matrices (i.e., better QoS level (P3) and higher monetary gain among PUs (P5)), and it requires proper coordination in which the PUs (or SUs) make decisions on the selection of SUs (or PUs) participating in spectrum leasing, so that both PUs and SUs mutually agree to fulfill each others requirements. For instance, in [8], the PUs choose the SUs that allocate higher transmission power to relay PUs' packets based on the bid values received from SUs through auction. The disadvantages are that the PUs incur high energy consumption while exchanging control messages and making decisions on the outcomes of auctions. Hence, a third-party auctioneer has been proposed to receive control messages from both PUs and SUs, as well as to make decisions on the auction outcomes [15]. Additionally, the purpose-built third-party auctioneer may reduce latency associated with auction because of the auction being its main and only task. Further investigation can be pursued to investigate a balanced trade-off between energy consumption and monetary gain in order to enhance the network performance of both the networks in the presence of a third-party auctioneer.

7.2. Investigating Distributed Spectrum Leasing Schemes.

Current research focuses on centralized networks (C1.1) in which PU BS and SU BS exist; however, this may not be the case in distributed networks (C1.2), and so further investigation can be pursued to investigate spectrum leasing in distributed networks. While there are investigations into distributed SU networks [8], this is not the case for PU networks in which most schemes in the literature assume the presence of a PU BS or a single PU node pair. The major challenge in distributed SU networks is that SU BS does not exist, and so the SUs must coordinate among themselves to determine a control channel for the purpose of control message exchange in spectrum leasing. The control channel is important for the exchange of control messages for spectrum leasing. The lack of a control channel has been investigated based on the assumption that the SUs are equipped with learning capabilities [8], specifically through past experience. Further investigation can be pursued to relax this assumption.

7.3. Implementation of Security Measures. Generally speaking, the implementation of security measures to prevent malicious SUs by PUs may increase the performance matrices (e.g., better QoS level (P3) and higher monetary gain by PUs (P5)). Since the PUs can provide continuous monitoring on SUs' channel access the PUs can detect malicious SUs. The challenge is to reduce the additional overheads, such as energy consumption, incurred by the PUs. This is particularly important because malicious SUs may access the channel (white spaces) in an illegitimate manner, and this minimizes the amount of white spaces for genuine SUs, which subsequently degrades the performance of PUs and SUs. Three examples of security vulnerabilities associated with spectrum leasing are as follows.

(i) SUs attempt to acquire the white spaces from PUs in an illegitimate manner through untruthfully raising their respective bid values (e.g., SU's transmission power used to relay PUs' packets) [15].

(ii) The winning SUs may further sublease their channels to losing SUs for monetary gain [15].

(iii) The SUs may launch collusion attacks in which SUs participating in an auction collaboratively reduce their bid values that may significantly reduce the monetary gain (P5) of PUs [7].

Further investigations can be pursued to address the aforementioned security vulnerabilities.

7.4. Investigating Energy-Efficient Spectrum Leasing Schemes. In spectrum leasing, the SUs may serve as relay nodes to transmit both PUs' and SUs' transmission packets; hence, they incur higher energy consumption. However, current literature primarily focuses on reducing energy consumption at PUs [8, 32] and so further investigation can be pursued to reduce energy consumption at SUs. By reducing the transmission power at SUs, there are two main advantages as follows.

(i) Firstly, it reduces the interference to PUs and its neighboring SUs, and this helps to enhance the PUs' and SUs' performance (e.g., better QoS level (P3)).

(ii) Secondly, it reduces SUs' monetary cost, which may be related to energy consumption used to relay PUs' packets [32].

Further investigation can be pursued to achieve a balanced trade-off in order to utilize the channel and energy in an efficient manner.

7.5. Investigating Common Assumptions of Spectrum Leasing. Future investigation can be pursued to relax the following common assumptions, as well as their effects, applied to the investigation of spectrum leasing in CRNs.

(i) Each node is equipped with two transceivers, namely, control transceiver and data transceiver. The control transceiver is always tuned to a single common control channel, which is available at all times; however, the existence of a common channel among nodes may not be realistic [13].

(ii) Each SU observes the similar white spaces, and the transmission from each SU can be observed by all of the other SUs [13]. This assumption may not be realistic because each SU may observe different white spaces.

(iii) Each SU BS makes decision on spectrum leasing. For instance, in [8], the SU BS makes decision for SUs' participation in spectrum leasing. However, the presence of a SU BS as a decision maker may not be feasible in distributed networks. There has been very limited literature on distributed approaches (see Section 7.2).

7.6. Defining the Selection and Eviction Criterion of SUs by PUs. Generally speaking, there has been very limited research on the selection and eviction criterion of SUs, which are used by PUs. This helps PUs to enhance the overall QoS performance (P3) of PUs' and SUs' networks. Two types of selection and eviction criterion are as follows.

(i) PUs may allocate white spaces to SUs that demand higher amount of white spaces in order to maximize their respective throughput and the monetary gain while neglecting other SUs that demand lower amount of white spaces.

(ii) PUs may monitor the SUs' activities so that PUs can evacuate SUs who breach the spectrum leasing contract upon negotiations [26].

Therefore, further investigation can be pursued to define the selection and eviction criterion in order to achieve higher network performance.

7.7. Implementation of Hybrid Model. Generally speaking, there has been limited research on the enhancement of QoS performance (P3) along with the monetary gain received by PUs (P5) in spectrum leasing. In the current literature, the exclusive-use model has been widely used in which PUs share their white spaces to SUs on lease for a definite period of time but cannot reclaim these white spaces even if the PUs encountered the shortage of spectrum, whereas, Kim and Shin [26] propose a hybrid model comprised of a shared-use model and an exclusive-use model. In shared-use model, SUs opportunistically use the spectrum while there is no advantage for PUs, neither in terms of monetary gain nor as an improvement of PU network enhancement. The inclusion of shared-use model gives PUs an additional privilege to evict the SUs whenever the PUs needs the white spaces for their own transmission. The challenge that arises in the hybrid model is the suspension of white spaces to SUs which is crucial for the PUs to fulfill their spectrum requirement at the expense of lower PU monetary gain due to deteriorating SU packet transmission. Further investigation can be pursued to investigate a balanced tradeoff that fulfills the PUs spectrum shortage as well as to ensure the minimum transmission requirements of SUs.

8. Conclusions

This paper presents a comprehensive review on spectrum leasing schemes along with the advantages, functionalities, characteristics, and challenges of each scheme in CR networks. Spectrum leasing schemes have been shown to address the concerns poised to the traditional CR networks, so that PUs can enhance their network performance and maximize their monetary gain, while the SUs can enhance their network performance through exclusive access to white spaces. Examples of PU's gains are monetary gain and network performance enhancement, while example of SU's gain is dedicated channel access. To achieve these gains, PUs need to determine the cost of the white spaces, the PU's and SU's channel access time, SU's selection as a relay nodes, and PU's own packet transmission, while SUs need to select the appropriate PUs according to the SUs' QoS requirements and the cost of white spaces, as well as to determine channel access time between SUs. In the literature, the network topology of PUs and SUs can be either centralized or distributed and the PUs and SUs operate among themselves using intracooperative and intercooperative modes, respectively. The challenges associated with PUs are the selection of the appropriate SUs to increase the monetary gain, the distribution of channel access time between PUs and SUs and continuous monitoring of SUs' activities, while the challenge associated with SUs is the selection of optimal channels in order to reap the benefits of spectrum leasing. Additionally, we discuss various performance enhancement achieved by the spectrum leasing schemes (e.g., lower outage probability and higher outage capacity). Finally, we recommend some open issues in order to spark new interests in this research area(e.g., enhancing auction and coordination mechanism and investigation of energy-efficient spectrum leasing schemes), as well as new kinds of CR networks such as CR sensor networks.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper. The views and opinions expressed in this paper are those of the authors and do not necessarily reflect those of the Malaysian Ministry of Science, Technology and Innovation (MOSTI).

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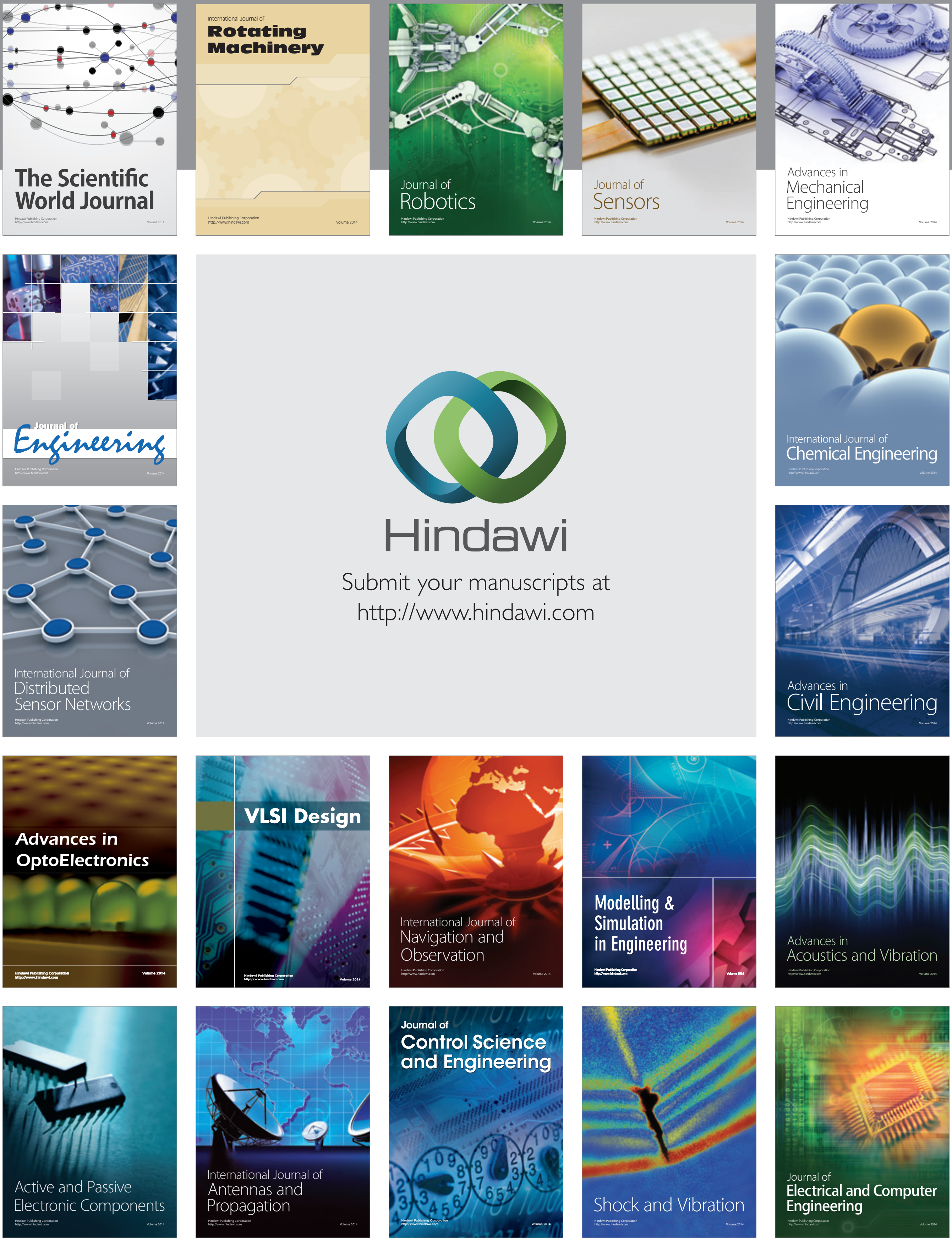

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