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A Survey on Dynamic Spectrum Access via Cognitive Radio: Taxonomy, Requirements, and Benefits

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Abstract Conventionally, interference protection among radio spectrum users is guaranteed through a policy of spectrum licensing that provides exclusive access to licensed users. However, as it is becoming extremely difficult to satisfy the growing demand for radio spectrum with this conventional policy, a flexible policy that can improve radio spectrum access and utilization without causing interference amongst users has recently gained increasing interest. In this context, this paper presents a comprehensive survey on flexible radio spectrum management with full focus on a cognitive radio technology application for dynamic spectrum access. The study approach involves analytical evaluation of the performance of the current fixed radio spectrum allocation policy examining both technical and economic perspectives. The result of which shows that the current fixed radio spectrum management policy is too rigid, inefficient and out-dated and needed to be replaced with a flexible radio spectrum management policy. Based on this analytical result, an in-depth survey on innovative technology and standards for a dynamic spectrum management model that can enhance an increase in spectral utilization and coexistence of multiple radios with adequate interference free communication was carried out. The paper also discusses the interrelationship between technologies, business and policies for cognitive radio standardization for seamless wireless communication. In addition, the paper presents both the technical and economic benefits of the dynamic radio spectrum management model over the current fixed radio spectrum allocation policy. The paper was finally concluded recommending the commercial adoption of dynamic spectrum access worldwide keeping in mind all the benefits of the dynamic spectrum access model and standards in place to ensure interference free communication in a cognitive radio environment.

Keywords Radio Spectrum, Spectrum Management, Cognitive Radio, Dynamic Spectrum Access, Spectrum Management Functions, Coexistence

1. Introduction

In wireless communications, the availability of radio spectrum is an indispensable key input. This is because radio spectrum is a principal component of wireless communications that supports today's information society. In the last two decades, wireless devices and applications have grown at an immensely fast rate. Mobile phones and wireless devices have outgrown fixed phones and wired devices respectively and reach deeply into lower income groups. Likewise, there are emergences of new wireless communications systems offering personalized services to users on the move. This trend which without any doubt is likely to continue according to [1], has led to a sporadic increase in demand for and use of radio spectrum worldwide.

Generally, with the tremendous growth in demand for and use of radio spectrum, the expectation is that its management and use should be more effective and efficient. However, the radio spectrum management policy has not kept abreast of these major changes in demand and the technology. Its management practices worldwide are still predicated on radio spectrum being a limited resource that must be apportioned among services and users by government agencies at both international and national levels. At national level, the radio spectrum is still partitioned into frequency bands, which are licensed to operators or licensed users for a long time. The license gives the holder the exclusive right to use the assigned frequency bands for providing radio services.

For over a century, the command-and-control radio spectrum management policy has worked well [1]. However, as radio spectrum comes under pressure as a result of rapid growth in wireless services, the demerits of a rigid and technology-specific allocation of the radio spectrum has cast a serious doubt on the suitability of the traditional fixed radio spectrum allocation policy. The demerits can be classified twofold: business and operational implications [2]. Under the business implication, the traditional fixed radio spectrum allocation policy has led to purpose-built networks that involve the capital intensive process of acquiring licensed spectrum as well as deploying network infrastructure and offering end-user services. This has made the process of acquiring licensed spectrum extremely slow and legalistic, causing a big player syndrome where only large service providers can compete for spectrum.

Under the operational implication, the traditional fixed radio spectrum allocation policy has been observed as the major cause of the current spectrum drought [3] since most of the licensed frequency bands actively transmit the information only for a short duration while certain portions of the licensed spectrum are idle when and where the licensed users are not transmitting [4-6]. This shows the imbalance the fixed radio spectrum allocation policy created between spectrum scarcity and spectrum underutilization. It also reveals the fact that the scarcity of Radio Frequency (RF) spectrum for wireless communications is not really as a result of a lack of usable radio spectrum but as a result of the inefficiency of the traditional fixed radio spectrum allocation policy.

With these noticeable demerits, it is obvious that the fixed radio spectrum allocation policy is not suitable for the increasingly dynamic nature of radio spectrum usage. Therefore, in order to accommodate future emerging wireless devices and applications, an essential requirement is the ability to access the radio spectrum on a dynamic basis and to be freed from the current technology-specific limitation imposed by the fixed radio spectrum allocation policy [1]. This leads to the idea of Dynamic Spectrum Access (DSA), which will increase both the radio spectrum availability and efficiency so that a larger density of wireless devices can be accommodated without creating new RF bands or re-assigning the already licensed RF bands. This approach also has other advantages. One of them is its flexibility as no limitations are put on technology and service. Another advantage DSA strategy will offer is the abrogation of bureaucratic processes involved in obtaining spectrum licences.

However, because radio spectrum is a broadcast medium, coexistence of two or more transmitters in the same frequency band usually results in interference among the users. Hence, a new class of radio that can coexist with other radio device(s) without causing interference to them by reliably sensing the spectral environment over a wide bandwidth in order to detect the presence/absence of the other transmitter(s) or user(s) and use the spectrum only when and where its usage will not interfere with the other users, is required for implementing DSA. In this paper, a comprehensive survey of cognitive radio technology for implementing DSA, and the functional requirements for cognitive radio to maintain no interference with other spectrum users, is provided. In particular, we discuss various standards or policies in place to ensure multiple radios coexistence reported in literature, since the success of DSA adoption hinges on reliable coexistence of multiple radio systems in a cognitive radio environment without harmful interference.

The paper is organized as follows: Section 2 presents background information on traditional spectrum management. We begin the section with information on radio spectrum and later provide a brief review of traditional radio spectrum management policy and why the policy needs to be reformed. Section 3 provides an in-depth review on different dynamic spectrum access models in the literature. In Section 4, we present a DSA technology enabler and its requirements. In Section 5 we present policies or standards for interference free communication in a cognitive radio environment. Some significant benefits of the DSA model over the traditional fixed radio spectrum allocation policy currently in operation are presented in Section 6. We finally summarize the paper in Section 7 and draw conclusions.

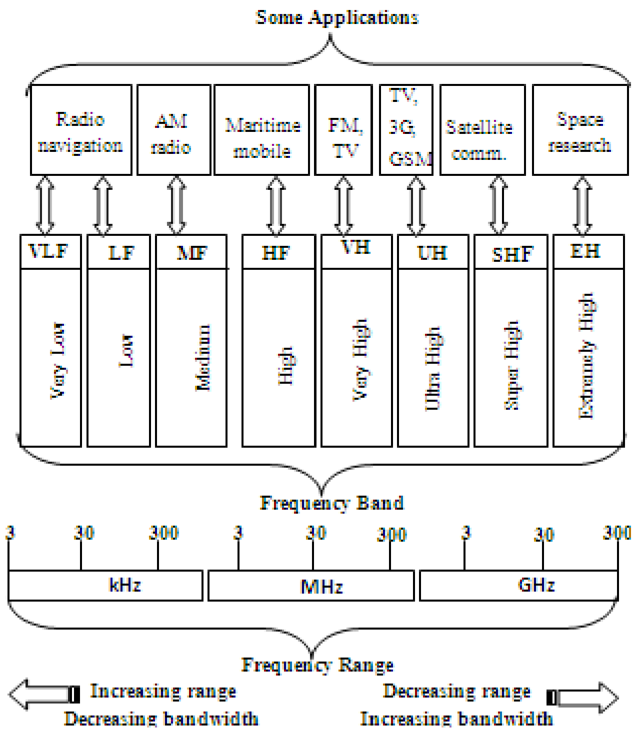

Figure 1. Radio Spectrum and some of its Applications (Adapted from [9])

2. Radio Spectrum Management and its Reforms

Radio spectrum is a natural resource with different parts of it being used for different purposes. Technically, radio spectrum is the only part of the electromagnetic spectrum that carries radio waves and suitable for wireless communications. Its boundaries are defined by frequencies of the transmitted signals and range approximately from 3 kHz to 3000 GHz as shown in Figure 1. It is a natural resource with some special characteristics [7]. According to [8], the major characteristics of the radio spectrum are their propagation features and the amount of information that signals can carry. According to these authors, signals sent using higher frequencies reach shorter distances, but have a higher information-carrying capacity. These physical characteristics of the radio spectrum limit the currently identified range of applications for which any particular frequency band is suitable. As shown in Figure 1, it follows that lower frequency bands are usually used for radio navigation or aeronautical services while satellite and space research services saturate the higher frequency bands. All the frequency bands can support mobile services. It is obvious from the figure that the most important mobile applications, such as GSM and 3G, are centred in the Ultra High Frequency (UHF) band. Other applications supported by UHF band are television (TV) broadcasting and Wireless Fidelity (Wi-Fi), and because of this frequency band's capability in support diverse wireless applications it is being referred to as "sweetspot" [9].

On the other hand, unlike most natural resources, such as iron, oil, coal, or other mineral resources, radio spectrum's unique characteristics is that it is not consumed by use. This means that the resource is infinitely renewable. Since it is renewable, radio spectrum cannot be accumulated for later use but must be properly managed. These factors therefore necessitate an efficient process for making radio spectrum available for purposes which are useful to society [8].

2.1. Traditional Radio Spectrum Management

Spectrum management is defined as the process of regulating the use of radio frequencies to promote efficient use and gain a net social benefit. It is an important aspect of telecommunications policy and regulation [8,10]. It stemmed from a set of basic international agreements concerning the allocation of various radio communications services in the radio spectrum [11]. Generally there are four activities involve in spectrum management: planning, authorization, engineering and monitoring.

- Spectrum planning involves the allocation of portions of the frequency spectrum to specified uses in accordance with international agreements, technical characteristics and potential use of different parts of the spectrum, and national priorities and policies.
- Spectrum authorization involves granting access under certain specified conditions to the spectrum resource by various types of radio communication equipment and the certification of radio operators.
- Spectrum engineering involves the development of electromagnetic compatibility standards for equipment that emits or is susceptible to radio frequencies.
- Spectrum monitoring and compliance involves the monitoring of the use of the radio spectrum and the implementation of measures to control unauthorized use [8].

The approach historically adopted around the world to manage radio spectrum has been highly prescriptive. It is the regulators that decided on the use of a particular range of frequencies as well as specifying what particular wireless services should be delivered in the band. This is referred to as the administrative approach to spectrum management, which the term "command and control" is also used to describe it. Under this traditional command and control radio spectrum management policy, the entire radio spectrum is divided into blocks or frequency bands for a particular type of wireless service by the process of frequency allocation. The frequency allocation is performed on an international and national basis. The only difference is that it is at the international level that high-level guidance, which national bodies adhere to, are usually set. Once allocation has taken place, assignment is the next stage of the spectrum management process. It is usually at the national level that the assignment is carried out. It is the final sub-division of the spectrum in which the spectrum is actually assigned to a specific party or operator to use. The primary tool of spectrum management at the national level is a licensing system. This involves spectrum being apportioned into blocks for specific uses, and assigned licenses for these blocks to specific users or companies. This "divide and set aside policy" grants exclusive right to use the assigned spectrum to licensed users on a long-term basis. The main advantage of the licensing approach is that the licensee completely controls its assigned spectrum and can thus unilaterally manage interference between its users and their quality of service. However, there has recently been numbers of identifying disadvantages of traditional "once and for all" means of allocation of radio spectrum. These disadvantages necessitate the recent call for radio spectrum management reforms.

2.2. Needs for Traditional Radio Spectrum Management Reforms

Technically, the traditional command and control approach in spectrum management through spectrum licensing has been an effective means of eliminating the danger of harmful interference, but it has led to highly inefficient use of the spectrum. This is because, the exclusive right to use the licensed spectrum at will has rendered the majority of this spectrum idle when and where the license-holder is not active. Another disadvantage of this policy is the impossibility of re-allocating spectrum to different technologies or other users who might have better use for the spectrum [1]. Other observed disadvantage of the approach according to [1] is that the allocation procedures were lengthy and bureaucratic, opening up the possibility that the decision-making process could be influenced by non-relevant factors such as higher bidders' syndrome making bidders to overstate their capabilities in their proposals to ensure they win the tender. These disadvantages and recent sporadic demand for and use of radio spectrum as well as wireless communications' contributions to the society coupled with the trend in technology, are some of the reasons necessitating the replacement of the current traditional radio spectrum management policy. Three out of some perceived factors that will soon force out the current traditional radio spectrum management policy are discussed in the following sub-sections.

2.2.1. Increase Demand for Bandwidth

With the current advent of high bandwidth multimedia services and applications as well as the growing demand for ubiquitous information network access for mobile wireless devices, it is obvious that there will be a continuous increase in demand for more bandwidth by both wireless services providers and users. This increase in demand for more bandwidth by both wireless services providers and users of wireless services and applications is one of the factors that will soon force the spectrum regulators worldwide to revise their policies regarding the usage and allocation of radio spectrum. This is because with the current traditional spectrum management, nearly all the usable radio spectrum has been allocated on exclusive use which will make availability of enough bandwidth practically not feasible for emerging wireless multimedia services and applications.

Currently, services like wireless broadband, Internet Protocol Television (IPTV) and many others applications that require much more bandwidth compared with most of the legacy services have been introduced [12]. Likewise, there are different types of Wi-Fi users including: office users wanting to save cabling expenditure and maintenance; household users wishing to enjoy internet connection in different places within the same residence; business users logging onto hotspots at airports; and students using university networks for research; that regularly require more bandwidth on a daily basis. In the next few years, wireless services and applications that even require much more bandwidth are likely to come into the main stream of wireless communication systems. Hence, in order to ensure availability of required bandwidth for these emerging bandwidth thirsty services and applications, reform of radio spectrum management is inevitable.

2.2.2. Current inefficient Usage of Licensed Spectrum

Under the current traditional fixed radio spectrum allocation policy, radio spectrum licensed owners usually pay to have exclusive access to certain portions of the spectrum. This policy as mentioned above has served well in the past especially in preventing interference amongst radio spectrum users. However, over the last twenty years, as the world experiences a proliferation of wireless services and applications, coupled with the increase in demand for and use of radio spectrum, a fixed frequency allocation policy has been observed as a major cause of radio spectrum scarcity. This stemmed from the imbalance the policy has created between radio spectrum scarcity and radio spectrum underutilization as a significant amount of licensed radio spectrum is sporadically used by licensed owners [13]. This underutilization of radio spectrum is not limited to certain nations of the world or frequency ranges but cuts across all nations, developed and developing, as well as different frequency ranges. This is revealed by a series of actual radio spectrum usage profiles carried out by different researchers in different parts of the world, at different frequency ranges.

For instance, a typical radio spectrum measurement carried out by the Enforcement Bureau of Federal Communications Commission (FCC) at Atlanta, Chicago and other parts of the United States (US), as reported in [14], shows that less than 11% of the licensed spectrum is used on average in US. In a similar measurement carried out by Defence Advance Research Projects Agency (DARPA), which was reported in [15], reveals that only 2% of the licensed spectrum is in use in the US at any given moment. Similar actual spectrum usage measurements of the 790 MHz – 862 MHz licensed spectrum carried out in Port Elizabeth, Johannesburg, Bloemfontein, Durban, Cape Town and Pretoria in South Africa by the Independent Communications Authority of South Africa (ICASA) in March 2009 revealed that 99.74%, 99.84%, 99.97%, 98.58%, 98.59% and 99.36% are the percentages of inactive frequencies respectively in those locations [16]. A similar actual measurement carried out and reported in May 2010 for 450 MHz – 470 MHz by ICASA in Port Elizabeth, Johannesburg, Bloemfontein, Durban and Cape Town showed that 0.37%, 2.0%, 1.75%, 0.81%, 0.67% and 0.67% are the respective usage percentages of the licensed frequencies in those locations at any time [17]. These series of measurements show that scarcity of usable radio frequencies for wireless communications is not as a result of a lack of radio spectrum but more likely as a result of the current inefficiency of the traditional fixed radio spectrum allocation policy.

2.2.3. Radio Spectrum Contribution to Economy and Poverty Reduction

Over the past decade, the use of radio spectrum has been a major contributor to Gross Domestic Product (GDP) and job opportunities in most developed and developing countries of the world. For instance, the economic impact of the use of radio spectrum to the United Kingdom (UK) was estimated to increase from around £20.3 billion in 2000 to £24.7 billion in 2002 and £28.1 billion in 2006 [18]. Likewise, African economics is also on growth path as a result of the use of radio spectrum. In 2007, for the fourth consecutive year, Africa’s real GDP growth rate exceeded 5%. Twenty-five Africa countries achieved a GDP growth rate of above 5% in 2007 while the GDP of another fourteen countries in the continent grew at a rate between 3% and 5% [19] as a result of the use of radio spectrum. The percentage contribution of wireless communication to South Africa real GDP at market price using the radio spectrum is shown in Figure 2. Similarly, Table 1 illustrates the contribution of the use of radio spectrum to the GDP of some other nations while Table 2 shows the contribution of Information and Communication Technologies (ICT) via radio spectrum usage to the global GDP from 2003 to 2007.

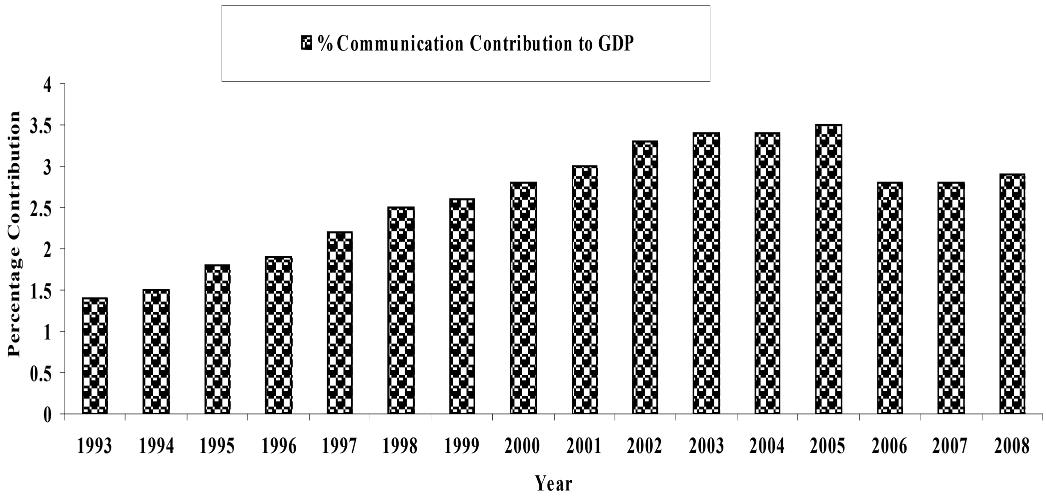

Figure 2. Percentage Contribution of Wireless Communication to South Africa Real GDP (Adapted from [20])

Table 1. Radio Spectrum Contribution to Some Nation's Economy (Adapted from [21])

Country	GDP Contribution in 2008
Malaysia	$26.5 billion
United States	$771.0 billion
UK	$39.9 billion
Ireland	$3.0 billion
Denmark	$3.2 billion

Table 2. Radio Spectrum Contribution to Global Economy [12]

Item	Year				
	2003	2004	2005	2006	2007
Telecom Services (%)	2.80	2.80	2.80	2.70	2.70
Telecom Equipment (%)	0.60	0.60	0.60	0.60	0.60
Software and Computer (%)	1.80	1.70	1.70	1.70	1.70
Computer Hardware (%)	0.90	0.80	0.80	0.80	0.80
Television Services (%)	0.70	0.70	0.70	0.70	0.70
Consumer Electronics (%)	0.60	0.70	0.70	0.70	0.70
Total (%)	7.40	7.30	7.30	7.20	7.20

In addition, radio spectrum as a primary asset underlies many aspects of human lives as a result of its importance in areas such as air travel, emergency services, cellular telephony, radio and television broadcasting and defence. With these contributions of radio spectrum to lives and global economy, radio spectrum management policy should be seen in the broader context of ICT, which has made great contributions to the world increasing productivity growth.

Based on advantages the radio spectrum offers, its management policy needs to be re-formed to enhance its sustainability. Its current management policy based on license control is out-dated and old fashioned. Since most parts of the radio spectrum can support more than one type of wireless services and applications, the current traditional spectrum management that gives a particular application preference over the others is too rigid, inefficient and out-dated. The allocation of the radio spectrum can now be left to market forces of demand and supply. It is high time the only technical considerations in spectrum management were supplemented with economic considerations in such a way that applications with a high value for the society are preferred to applications with a lower economic value.

Though the capability of the current spectrum management policy in eliminating the danger of radio interference has been one of the factors being used to support arguments for traditional radio spectrum management [22], the advent of Cognitive Radio (CR) that can eliminate the inconvenience of radio interference will indeed provide a better alternative to the current traditional spectrum management policy. Cognitive radio as observed is a promising technology that can provide radio signal non-interference based on its built-in capabilities. Apart from the potential to eliminate radio interference, CR also has the ability to enhance more efficient use of the spectrum as well as providing flexibility to spectrum usage by its ability to adapt to different radio environments. The CR system, therefore, can play an important role in achieving DSA and thereby provides a paradigm shift from the current fixed spectrum allocation policy to a dynamic spectrum management model. A brief review of CR as an enabling technology for DSA is presented in Section 4 of this paper while a different taxonomy of DSA models is presented in Section 3.

3. Taxonomy of Dynamic Spectrum Access Models

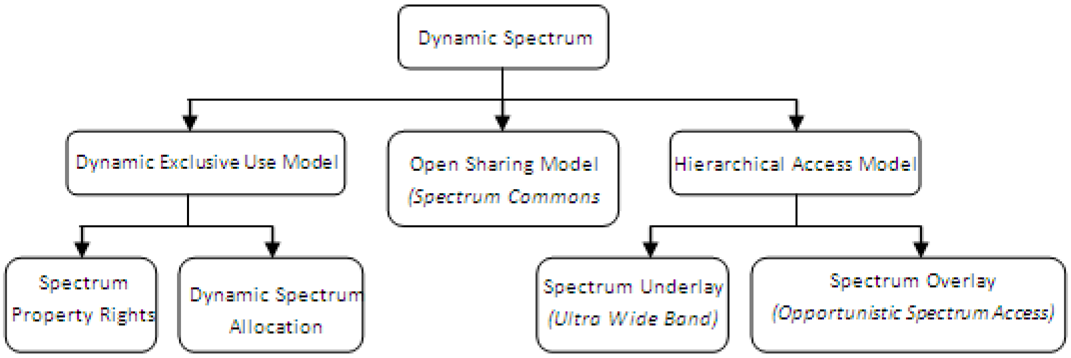

Figure 3. Taxonomy of Dynamic Spectrum Access [25]

Figure 3 illustrates the taxonomy of DSA models. As shown in Figure 3, DSA strategies are classified under three broad models [23-25]: dynamic exclusive use model, open sharing model, and hierarchical access model.

3.1. Dynamic Exclusive Use Model

Under this access model, only one user is permitted at any given point in time and location to use the spectrum. The access model maintains the current radio spectrum access strategy whereby frequency bands are licensed to users or licensed owners. The licence gives the owner the exclusive right to use the frequency band for specified wireless services in a defined geographical area. However, observations have shown that the licensees do not utilized the allocated spectrum band all the time. Thus the idea of sub-leasing their frequency bands when not in use was proposed. As reported in [23-27], two sub-lease approaches were proposed: spectrum property rights and dynamic spectrum allocation.

Under the spectrum property rights, the licensed owners are allowed to own and use their licensed spectrum as they see fit and to lease or sell their property and receive the income it generates. This access model gives a sub-licensee the exclusive right to use the sub-lease spectrum without being mandated by a regulatory body. In this approach, under the dynamic exclusive use model, the licensed or primary owner assumes the role of a spectrum regulator and the lessee with transferred license reports back to the primary owner all matters relating to the lease spectrum.

In a dynamic spectrum allocation model, which is the second approach of sub-leasing an already allocated frequency band under the dynamic exclusive use model, both the spatial and temporal traffic statistics of different services are exploited [27]. This access strategy, which is based on dynamic traffic statistics, provides a much more flexible spectrum allocation than spectrum property rights. However, because dynamic allocation is limited to the capabilities of the licensed owner, it is obvious that none of these two approaches for dynamic exclusive use model can eliminate current underutilization of the radio spectrum [23-25].

3.2. Open Sharing Model

This access model is different from the dynamic exclusive use model because the model does not require a user to have a license before transmitting on a certain part of the radio spectrum. The model is therefore referred to as spectrum commons [23-27]. This implies that any user can own any number of devices operating in such a band. Examples of open sharing or spectrum commons are current 2.4 GHz called the Industrial, Scientific and Medical (ISM) frequency band and 5 GHz called the Unlicensed National Information Infrastructure (UNII) frequency band. However, like in the dynamic exclusive use model, two different approaches are employed in ensuring interference free communication in this model.

The first approach proposed and investigated by [28], involves using a centralized sharing strategy called a Spectrum Policy Server (SPS), which performs the centralized allocation of the available spectrum in a geographical area. The function of a SPS is twofold: one to mediate spectrum sharing among communicating devices and two to monitor the relevant spectrum. The second approach for ensuring interference free communication in this open sharing model is a distributed sharing strategy, which was proposed and examined in [29]. Collision avoidance or interference avoidance under this approach is achieved either by negotiation or using collision avoidance techniques such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) or random back.

3.3. Hierarchical Access Model

This access strategy is the third category of the dynamic spectrum access strategy. It is a hybrid of the first two dynamic spectrum access models. It is built on the premise of a hierarchical spectrum access right. The two structural hierarchical spectrum access rights involved are: primary user or higher priority user and secondary user or lower priority user. The primary user is defined as the licensed owner of the spectrum that can access the spectrum at any time without any interference, while the secondary user is an unlicensed user of the spectrum that only accesses the spectrum when and where its transmission will not interfere with the primary user. The basic idea of this access model is to increase radio spectrum utilization efficiency by allowing spectrum sharing between licensed or primary users and unlicensed or secondary users in a non-interference manner. Like the other two DSA access models, there are two approaches to this access strategy model: spectrum underlay and spectrum overlay.

In a spectrum underlay access strategy, concurrent transmission in the manner of an Ultra-Wide Band (UWB) system by both primary and secondary users is allowed. However, this secondary spectrum access strategy protects the primary users by enforcing a spectral mask on the secondary signals so that the interference generated by the secondary users is below the acceptable noise floor for the primary users of the spectrum. Hence in such systems, the secondary user can always access the spectrum subject to the interference threshold constraint. However, satisfying the interference constraint is technically challenging [30], since the interference power constraints associated with an underlay access strategy only allow short range communications [31]. In addition, in underlay spectrum sharing, the secondary user must satisfy the interference threshold condition even when the primary user is idle. During this idle period, fulfilling the interference constraint limits of the transmission power of the secondary user reduces its achievable transmission capability. More so, in an underlay access strategy, the achievable capability of the secondary user is further reduced during the busy periods of the primary user because of the interference imposed by the primary user activity at the secondary user's receiver. So to tackle these aforementioned issues, overlay spectrum sharing was proposed.

In overlay spectrum sharing, access to the spectrum is based on the idea of opportunistic communication, whereby the secondary user only accesses the licensed spectrum whenever the primary user is idle and leaves the channel before the primary user reappears on the channel. This access strategy requires that the secondary user senses the spectrum to ascertain the absence/presence/reappearance of the primary user so as not to cause interference to the primary user. Whenever the primary user reappears on the channel, the secondary user is expected to stop transmission and vacate the channel immediately. In other words, this spectrum access sharing strategy is permitted only in temporal frequency voids, referred to as spectrum holes or white spaces that are not in use by licensed owners. This spectrum access strategy is often called Opportunistic Spectrum Access (OSA) or Dynamic Spectrum Access (DSA) [32].

3.4. Analysis of Dynamic Spectrum Access Taxonomy Models

DSA taxonomy models as mentioned above are different access strategies by which dynamic spectrum access can be achieved. As discussed above, methodologies employ in those models vary from one model to another. Unbiased analysis of the models presented in Table 3 shows their respective strengths and weaknesses. Based on the analysis result, we acknowledge the spectrum overlay access strategy under the hierarchical access model as the best DSA model taxonomy and the appropriate model upon which the remainder of this paper focuses.

Table 3. Analysis Result of Taxonomy Models

Parameter	Taxonomy Model					
	Dynamic exclusive use		Open Sharing		Hierarchical access	
	Spectrum property rights	Dynamic spectrum allocation	Centralized sharing strategy	Distributed sharing strategy	Spectrum underlay strategy	Spectrum overlay strategy
Number of user per time	One	More than one	More than one	More than one	More than one	More than one
Does model support rigidity?	Yes	No	No	No	No	No
Does model support flexibility?	No	Yes	Yes	Yes	Yes	Yes
Model interference control policy	Primary license	Secondary license	SPS	CSMA/CA	Mask with interference threshold constraint	Spectrum sensing technique/CR standards
Can model eliminate spectrum under-utilization?	No	No	Partially	Partially	Partially	Perfectly or completely
Spectrum portion for dynamic spectrum access communication	Limited to only one application frequency band	Limited to only one application frequency band	Limited to only one application frequency band	Limited to only one application frequency band	Limited to only one application frequency band	Any available temporal frequency band called spectrum holes

4. Dynamic Spectrum Access Enabler and Requirement

Cognitive Radios (CRs) are enabling technology for DSA [4,6,33-35]. Unlike conventional radios, CRs have the capability to sense their environment and proactively change their mode of operation as required [32]. It is an intelligent radio that is cognizant of its environment [36], learns from it and adapts transmission features according to statistical variations in the environment to optimize radio spectrum utilization. CR arises as a promising solution to improve effective utilization of the radio spectrum by allowing an unlicensed or secondary user to opportunistically access unused portions of the licensed spectrum provided that such an opportunistic access will not cause interference to the primary owner or user.

In a DSA strategy, the crucial challenges of CR technology are how the secondary user can:

- Determine which frequency band is available and detect the presence of a primary user when the primary user is operating in a licensed band or detect the primary user re-appearing after the secondary user has commenced communication,
- Select the appropriate available frequency band according to the spectrum characteristics and user quality of service requirements,
- Coordinate access to the available frequency band with other users, and
- Quickly vacate the frequency band when a primary user is detected.

These four operations that are needed to allow a CR to adapt to the dynamic spectrum environment form a cognitive cycle [6,37,38]. As shown in Figure 4, the stages of the cognitive cycle consists of the above four operations, which are referred to as spectrum management functions [6,38]. The four spectrum management functions are respectively: spectrum sensing, spectrum decision or management, spectrum sharing, and spectrum mobility [6.38,39].

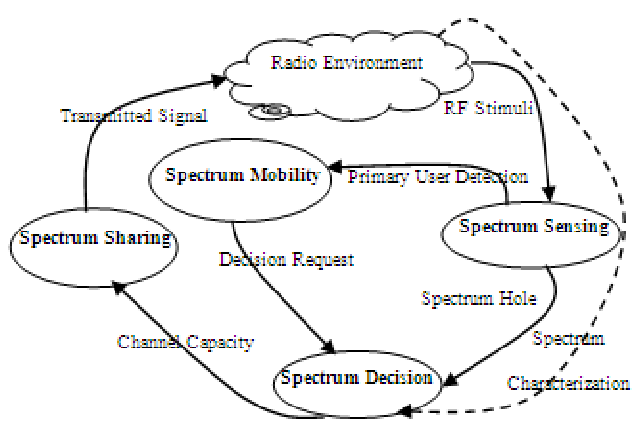

Figure 4. Cognitive Cycle (Akyildiz, Lee, and Chowdhury, 2009)

Although all four spectrum management functions' stages are interconnected, as shown in Figure 4, spectrum sensing has been identified as the main functional stage in the CR environment and is thus closely related to the other spectrum management functions [6,38]. The essence of spectrum sensing is to ensure interference-free communication between the secondary and primary users. The interference-free communication is achieved by scanning the corresponding band for some time and to detect whether any radio signal is present [40]. If no signal is detected, it may therefore be concluded safe for a secondary user to begin transmission. Based on its importance, technical approaches to spectrum sensing have been an active research area in recent years. On a policy angle to ensure interference free communication in a cognitive radio environment, various CR/DSA standardizations had been formulated. Detailed reviews of these policies or standards are presented in Section 5.

5. Standards for Cognitive Radio

The reforms in radio spectrum access and management in response to changes in demand for and use of radio spectrum cannot be successfully managed without rules or standards that can ensure interference free communications between users. In this context, substantial numbers of standards have been proposed and developed by different bodies for dynamic spectrum access based technologies. Standardization organizations such as International Telecommunications Union-Radio (ITU-R) Sector, Software-Defined Radio (SDR) Forum and Institute of Electrical and Electronic Engineering (IEEE) are a few of bodies working on CR standards. Efforts by these bodies are incoherent initially due to a lack of common understanding. Hence, to foster DSA deployment via CR, the IEEE Standards Coordinating Committee (SCC) 41, IEEE SCC41, known as Standards Committee on Next Generation Radio and Spectrum Management has initiated a series of standards known as the IEEE 1900 series.

However, having realized the benefits of coordinated work around CR standardization, the IEEE 1900 Standards Committee was established in first quarter of 2005, jointly by the IEEE Communications Society and the IEEE Electromagnetic Compatibility Society. The objective of this task force was to develop supporting standards that would deal with new technologies and techniques for next generation radio and advanced spectrum management. Finally, according to [41], on March 22, 2007, the IEEE Standards Board approved the reorganization of IEEE 1900 effort as SCC 41 on Dynamic Spectrum Access Networks (DySPAN).

5.1. IEEE SCC41 Structure

The belief of IEEE SCC41 is that CR standardization should be an interactive process comprising of technologies, business cases and policies [42], as shown in Figure 5. The essence of this is to enhance perfect CR standardization. For instance, service providers or manufacturers (business cases) that will provide new devices that will meet users' requirements will promote technology developmental activities. Such business motivation(s) must also be based on policies that are environmental friendly and in accordance with the regulation. Hence, the effect of technologies on CR standardization will drive industries and academia towards finding new efficient methods of utilizing radio spectrum.

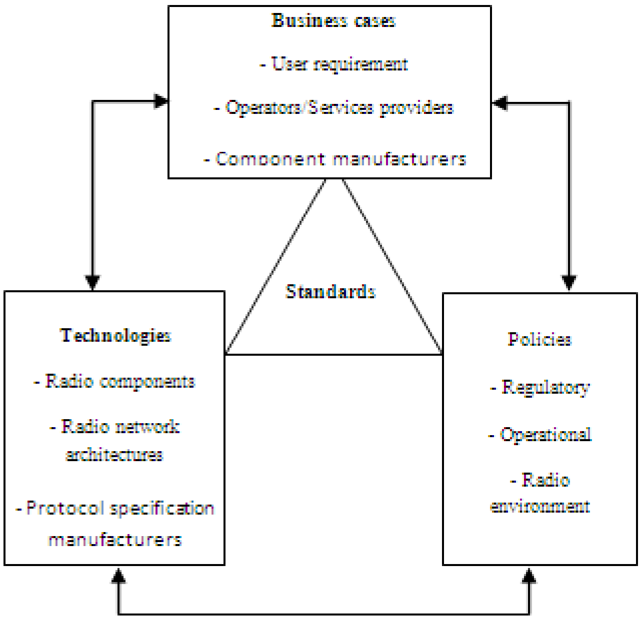

Figure 5. Interrelationship between technology, policy and business in CR standardization [42]

Similarly, it is obvious that technology alone cannot support all the requirements the new business cases will generate. Though it can provide what can be done and how it will be done, it will not provide strategies involved in reaching out to the customers or end users. Therefore, the strategies involved in reaching the end users can only be achieved through new initiatives in regulatory procedures or policies provided by spectrum regulatory agencies. Also, as the communication world is growing completely wireless, an increasing demand for and use of radio spectrum for diverse emerging devices from industry will flood the market. As a result, the development of efficient techniques for maximizing radio spectrum usage and access is essential. Therefore, the consumers or users requirements will drive new business cases, which also will drive the need for more radio spectrum. Hence, extra efforts in re-use of radio spectrum and standardization of devices will generate business opportunities for manufacturers and service providers. Therefore, the three components need to be coherent for effective CR/DSA standardization.

5.2. IEEE SCC41 Building Block

Within IEEE, an area known as coexistence [43], which is related to CR has been considered for some years. The idea of coexistence is that different radios must possess the ability to coexist with other radios in the same frequency by using different protocols. This coexistence policy is exactly the policy operating in open sharing model/spectrum common or unlicensed frequency bands, Figure 3, where a wide variety of unrelated protocols are applied such as IEEE standards like IEEE 802.11, IEEE 802.15 and IEEE 802.16. Particularly, techniques such as power control and dynamic frequency selection were developed and standardized to deal with coexistence issues. These coexistence techniques developed for these bands are similar to those for DSA. In this regard, related standards for CR, picture CR/DSA techniques as an evolution of coexistence techniques.

Though coexistence according to [43] does not require the use of cognitive techniques, but cognitive techniques can be used to facilitate coexistence. Hence, all completed IEEE 802.x standards that deal with coexistence were used as building blocks for IEEE SCC41 standardizations as shown in Figure 6 because they provided information on what constitutes interference and mechanisms to mitigate it. They also provided background information on automated detection and spectrum sharing techniques applicable in CR/DSA. A synopsis of IEEE 802.x standardizations are presented in Table 4.

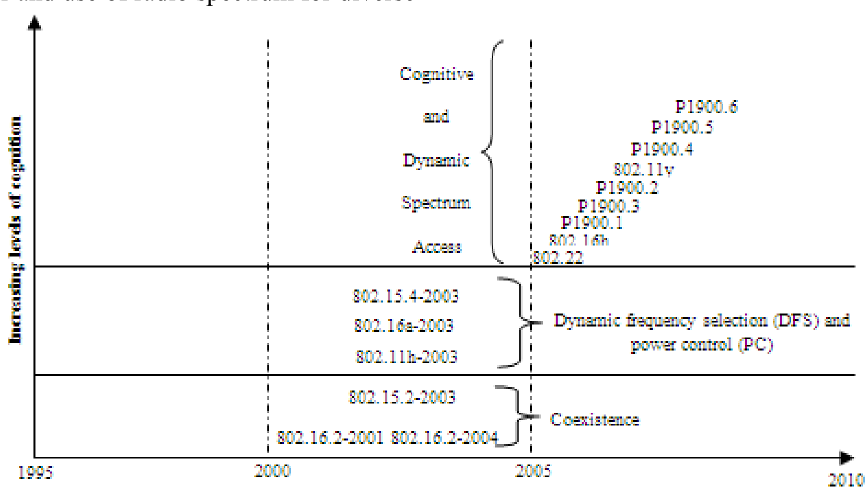

Figure 6. Evaluation of IEEE Standardization Activities from Coexistence to DFS/PC and finally to CR/DSA (Adapted from [43])

Table 4. A synopsis of IEEE 802.x standardizations relating to CR, DSA and coexistence technologies (Adapted from [43])

Standard	Scope
IEEE 802.16.2-2001 Initiation: 9/1999 Completion: 11/2001	It is one of the coexistence standards. It provided guidelines for minimizing interference in fixed broadband wireless access systems. It also addressed pertinent coexistence issues and recommended engineering practices, as well as providing guidance for system design, deployment, coordination, and frequency usage. It applications covers frequencies of 10 – 66 GHz in general, but focused on 23.5 – 43.5 GHz. However, it has been superseded by IEEE 802.16.2-2004.
IEEE 802.15.2-2003 Initiation: 1/2000 Completion: 6/2003	This standard provides recommendation practice for coexistence of IEEE 80.15TM wireless personal area networks with other selected wireless devices operating in spectrum commons or unlicensed frequency bands. The standard equally suggests recommended practices for IEEE Std. 802.11TM, 1999 edition devices to facilitate coexistence with IEEE 802.15 devices operating in spectrum commons bands. It also suggests modifications to other IEEE 802.15 standards in order to enhance coexistence with other selected wireless devices operating in spectrum commons or unlicensed frequency bands.
IEEE 802.15.4-2003 Initiation: 12/2002 Completion: 5/2003	This standard defines the appropriate protocol and interconnection of devices via radio communication in a personal area network. It uses carrier sense multiple access with collision avoidance (CSMA/CA) medium access mechanism and supports star coupled with peer-to-peer topologies. The standard includes dynamic channel selection and operates at low power, among other techniques, in order to support coexistence with other radio or wireless devices.
IEEE 802.11h-2003 Initiation: 12/2000 Completion: 9/2003	This standard is an amendment to the IEEE Std. 802.11-1999. It provides mechanism for dynamic frequency selection and transmits power control that may be used to satisfy regulatory requirements for operation in the 5 GHz Wi-Fi band in Europe as well as other regulatory domains. However, the standard has been superseded by IEEE Std. 802.11-2007.
IEEE 802.16a-2003 Initiation: 2/2002 Completion: 4/2003	This standard is an amendment to the IEEE 802.16-2001standard. It expands IEEE 802.16-2001standard scope by extending the wireless metropolitan area network air interface to address operational frequencies from 2 – 11 GHz. The standard also added dynamic frequency selection and transmits power control techniques. In addition, the standard includes an Annex (B.2) that discusses coexistence in spectrum commons bands and provides interference analysis.
IEEE 802.16.2-2004 Initiation: 9/2003 Completion: 3/2004	This standard is a reversion of IEEE 802.16.2-2001. The standard added treatment of coexistence in the 2 – 11 GHz frequency bands to the earlier IEEE 802.16.2-2001 standard.

5.3. IEEE SCC41 Standardization Overview

As shown in Figure 7, IEEE SCC41 is divided into six Working Groups (WGs) and two Task Groups (TGs). Each of these working groups is responsible for evolving standardization processes for different aspects of CR. The WGs are identified as IEEE 1900.x, where .x stands for one of the WGs. Each of the WGs submitted a document to IEEE based on the term of reference, which was finalized by the IEEE Standards Association (SA). The standards created by each of these WGs are reviewed as follows:

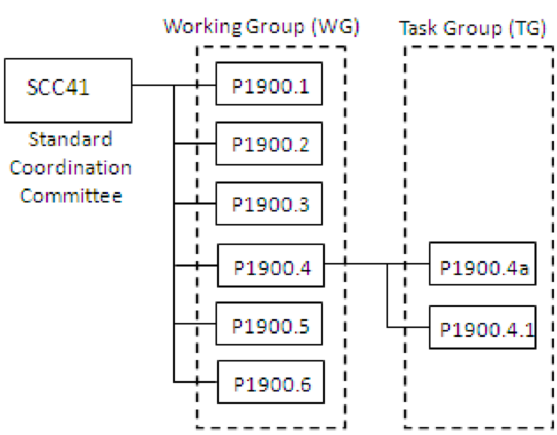

Figure 7. SCC41 Working Groups [41]

5.3.1. IEEE P1900.1 Working Group

The responsibility of this WG is to create standard definitions and concepts for spectrum management and advanced radio system technologies. The main idea is to standardize and explain technically precise definitions related to CR. From this WG, a standard which provides technically precise definitions and explanations of key concepts in the field of spectrum management, policy defined radio, adaptive radio, SDR, and related technologies was created. The standard from the WG also provided descriptions on how these technologies interrelate as well as how they can be used in a wide variety of communication service environments to achieve new capabilities while at the same time providing mechanisms supportive of new spectrum management paradigms and DSA.

Before the IEEE P1900.1 WG standard was released, some terms in the field of CR and DSA were defined differently depending on author(s). For instance, CR was defined by Mitola III in his Ph.D thesis as “the point in which wireless personal digital assistants (PDAs) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs [44]”. On the other hand, the SDR Forum defines it as “an adaptive, multi-dimensionally aware, autonomous radio (system) that learns from its experiences to reason, plan, and decide future actions to meet user needs". The same term was defined by [4] as "an intelligent wireless communication system that is aware of its surrounding environment (i.e., outside world), and uses the methodology of understanding-by-building to learn from the environment and adapt its internal states to statistical variations in the incoming RF stimuli by making corresponding changes in certain operating parameters (e.g., transmit-power, carrier frequency, and modulation strategy) in real-time, with two primary objectives in mind:

- highly reliable communications whenever and wherever needed
- efficient utilization of the radio spectrum."

These series of ambiguities in use and defining CR terms necessitate having common definitions and explanation for glossary of CR oriented terms. The common definition/standard by IEEE P1900.1 defines CR as "a type of radio that can sense and autonomously reason about its environment and adapt accordingly. This radio could employ knowledge representation, automated reasoning and machine learning mechanisms in establishing, conducting, or terminating communication or networking functions with other radios." Cognitive radios can be trained to dynamically and autonomously adjust its operating parameters." This standard, which emanated from IEEE P1900.1 WG took care of these ambiguities. The IEEE P1900.1 standard, according to [45] was published in September 2008.

5.3.2. IEEE P1900.2 Working Group

The essence of this WG is to provide a recommended practice for interference and co-existence analysis. The WG was formed because radio spectrum is a broadcast medium. Hence, when many radio systems co-exist and try to maximize the utilization of the spectrum, how to ensure interference free communications is usually a crucial requirement. The WG mandate, therefore, was to recommend the interference analysis criteria and establish a well-thought-out framework for analyzing the interference between radio systems. Thus, the standard emanated from this WG and published in July 2008 [45], provides technical guidelines for analyzing the potential for coexistence of radio systems operating in the same frequency band or between different frequency bands. The standard provides a common platform on which the disputing parties can present their cases and resolve them amicably.

5.3.3. IEEE P1900.3 Working Group

The mandate of IEEE P1900.3 WG is to provide a standard for assessing the spectrum access behavior of radio systems employing DSA methods. The WG responsibility therefore is to develop the standard that will specify techniques for testing and analysis to be used during compliance and evaluation of radio systems with DSA capability. The WG will also develop the standard to specify system design features that simplify the evaluation challenge. The WG is still working on their mandate.

5.3.4. IEEE P1900.4 Working Group

As reported in [46], the IEEE P1900.4 WG was formed in February 2007 from the 1900.B study group [47] to standardize architectural building blocks enabling network-device distributed decision making for optimized radio resource usage in heterogeneous wireless access networks [41]. The main objective of the WG is to increase the overall system utilization of reconfigurable terminals while increasing the perceived quality of service. This is to ensure that all IEEE P1900.4 enabled devices operate in an opportunistic and dynamic manner such that they will not degrade the performance of primary radio access devices.

The IEEE P1900.4 standard was published on 27th February, 2009 [45]. The WG had also served as the task force on two additional standards, as shown in Figure 7. One of the task forces, P1900.4a, developed an amendment to the original standard which defines the architecture and interfaces for DSA networks specifically in white space frequency bands. Similarly, P1900.4.1 creates a standard for interfaces and protocols that enables distributed decision making for optimized radio resource usage in heterogeneous wireless networks.

5.3.5. IEEE P1900.5 Working Group

This is the WG on policy language and policy architectures for managing CR for DSA applications. The purpose of the WG, therefore, is to define the standard on policy language or a set of policy languages or dialects to specify interoperable, vendor-independent control of CR functionality and behavior for DSA resources and services. This standard also defines architectural views of policy components interaction.

5.3.6. IEEE P1900.6 Working Group

The IEEE P1900.6 Working Group is the WG on the standards on interfaces and data structures for exchanging spectrum sensing information for DSA systems. The standard defines information exchange between spectrum sensors and their clients in radio communication systems. The logical interface and supporting data structures used for information exchange are defined abstractly without constraining the sensing technology, client design, or data link between sensor and client [45].

6. Benefits of Dynamic Spectrum Access

Technology is futile without a relevant application. Out of many applications for CR, DSA has been the most recognized application of CR. As mentioned earlier, DSA is a decentralized approach to a spectrum allocation policy that allows a communication device to operate on any unused spectrum. In this new paradigm, unlicensed or secondary users can opportunistically operate in an unused licensed spectrum, as long it does not cause interference to the licensed or primary users. Some significant benefits that have been attributed to DSA are presented in the following sub-sections.

6.1. Spectrum Utilization Efficiency

The major factor that has elevated the increase in interest currently experienced with CR technology is its potential for improving spectral utilization efficiency through spectrum sharing. Currently, spectrum sharing is restricted to simple approaches such as low-power unlicensed devices [48]. However the new types of spectrum sharing with DSA technology will enable higher-power transmission at times that the licensed owners of the frequency bands are inactive.

This includes real-time trading of spectrum access rights, and collaboration among unlicensed users to more efficiently share the spectrum. This technology will help in mitigating the radio spectrum scarcity problem currently being experienced and enhance availability of spectral resources for future emerging wireless services and applications.

Similarly, the recent developments in spectrum policy and regulation, especially the release of the National Broadband Plan (NBP), the publication of final rules for television white spaces, and the ongoing proceeding for secondary use of the 2360-2400 MHz band for medical body area network according to [49], allows more flexible and efficient use of radio spectrum. The developments have started yielding results as the presence of television white spaces (TVWS) in the European Union (EU) currently present a unique opportunity for proving high-speed Internet access to its citizens [50]. According to these authors, one of the benefits of deploying Super-WiFi in the TVWS compared to conventional WiFi is range extension. For instance a free space loss formula suggests that usage of the 2.4 GHz band allows a maximum transmission range of 250 m. However, usage of the TVWS band, would allow a maximum transmission range of 1.2 km, which according to these authors is a significant range benefit at the maximum sustainable connection rate of 54Mbps. In addition, the authors also proved that TVWS provides higher capacity and radio coverage than present network operators' bands of Universal Mobile Telecommunication System (UMTS). They showed that in the 2 GHz scenario, the coverage probability is 94% with average throughput 15.2 Mbps whereas in the TVWS scenario, the coverage probability increases to 100% with average throughput of 16.9 Mbps, which provide a significant increase in system capacity. All these benefits are obtained because of the existence of DSA, which leads to radio spectrum availability and efficient utilization.

6.2. Market-friendly Spectrum Sharing

DSA is of high economic value [51] since not only can it enhance spectrum utilization efficiency, but it would also introduce new customer-oriented wireless services that can provide the licensed owner with extra revenue via spectrum trading, which is the process of selling and buying radio spectrum in a cognitive radio environment. Under the current fixed spectrum allocation policy, the government controlled spectrum regulators set the spectrum usage rules and determine the type of wireless services for frequency bands. But under DSA, the flexibility involved permits a dynamic spectrum market where licensed owners can lease out their channels to generate revenue whenever their spectrum is underutilized, as long as the secondary user will not introduce interference to the licensed owner.

Currently, there are two major marketing strategies involved in radio spectrum trading: single seller and multiple sellers. In single seller approach, which is also known as monopoly market, only a single seller is involved. Hence, the seller or the licensed owner of the underutilized spectrum can maximize its revenue per time depending on the demand rate from the buyer or secondary user(s) requesting for spectrum. In order to control the market, buyers can either compete or cooperate to buy the spectrum opportunities. According to [52], either of these approaches, i.e. competition or cooperation, affects the revenue of the seller. On the other hand, in multiple sellers or oligopoly market, there are multiple sellers offering their unused radio spectrum for sale at the same time. This gives individual buyer choice to choose the best offer to maximize its satisfaction both in terms of price and performance.

Generally, in spectrum trading, the primary objective of a licensed owner or underutilized spectrum seller is to maximize revenue, while that of a secondary user or buyer is to maximize the utility of the radio spectrum usage [52]. Hence, as the underutilized spectrum radio seller increases the price in order to generate more revenue, the utility of the buyer will decrease due to higher cost involve. These disparities in objectives regularly do create conflict between the two parties involved in spectrum trading. Five suggested techniques, reported by [52] in order to obtain an optimal and stable solution for the spectrum seller and buyer whenever spectrum trading is being modeled are microeconomic approach, classical optimization approach, non-cooperative game approach, bargaining game approach and auction approach. Above all, this market-friendly spectrum sharing does not only generate income for the licensed owners but also enhances service satisfaction for the secondary or unlicensed users.

Conventionally, trading of radio spectrum rights can take several forms. In a sale format, ownership of the radio spectrum right is permanently transferred to the buyer. Under buy-back format, the radio spectrum right is sold to another user with an agreement to buy it back at a given date. In addition, trading of radio spectrum right can be through leasing, which transfers the right to exploit the radio spectrum to another user for a defined period but the ownership and control of the radio spectrum right still remains with the primary owner or user of the spectrum. Under mortgage trading format, radio spectrum right can be use as collateral for a loan. In all of these radio spectrum right formats, the ultimate objective is to maximize spectrum sharing as well as the economic value of the radio spectrum in a friendly manner.

6.3. Enhance Cost-effective Access

Another benefit of DSA is its ability to enable cost-effective access to preferred or lower frequencies. For instance, DSA-enabled secondary users can access the television white spaces (TVWS) for free. These lower frequencies allow the operator to dramatically decrease site deployment costs because radio spectrum signals propagate at these lower frequencies cover greater distances. Though the information carrying capacities of the signal at these lower frequencies are small, its application in rural areas can enable a given area to be covered with fewer base stations and less infrastructure. A cost analysis of this benefit presented in Shared Spectrum Company, [53], shows that if a base station costs $0.35 million to deploy a single 700 MHz site, the same site will cost the service operator deploying in above 1 GHz frequency band between $1.4 and S3.5 million. This is a typical illustration of DSA cost effectiveness.

Another area where DSA enhances cost-effective access is in its ability to use free and leased spectrum as well as its capability to use existing radio towers and infrastructures. This enables smaller scale, lower entry costs become feasible to drive down the service prices. These lower entry costs increase the introduction of new wireless products and services in the marketplace. Among the method of sharing wireless connectivity presently practiced for instance in the US, are sharing network facilities, sharing network operations and sharing of radio spectrum. Few examples of such communication resource sharing include nationwide roaming, selling packages of minutes purchased from a facilities-based network, leasing network capacity and spectrum access from a facilities-based network to create a new service provider known as a Virtual Mobile Network Operator. Generally, in all these resource sharing methods, access is leased from an owner of the communication resource such as a tower or antenna or radio spectrum license. Likewise, in Europe, with the current increase in the cost of building out network capacity to accommodate mobile broadband, some wireless operators notably in the European Union are now entering into cooperative agreement to jointly own and build networks. In this situation, each operator or service provider operates on its own frequency while sharing other network resources.

This cost-effective access methodology provided by DSA does not only improve broadband communication system but also promote job opportunity as well as contributing to the nations' economy. Also, these lower entry costs provided by DSA according to [48] will increase the pace of both product and business model lifecycles through faster entry and exit in the market place. The authors also observed that DSA under this cost-effective access allows new services to replace legacy services more gracefully providing varieties of services and opportunities. Also, the lower cost entry feasibility will enhance competition business communication services and driving down service prices. This will also make the incumbent or legacy business models built around spectrum scarcity to be less viable. Hence, the cost-effective access opportunity created by DSA will stimulate innovation(s) communications even from primary operators who do not exploit it.

However, it was observed by [48] that the lower entry cost might make it extremely difficult for the primary or legacy service provider(s) to recover the fixed costs associated with introducing new technologies and services. They also pointed out that lower entry costs are capable of increasing the likelihood that successive generations of technologies will overlap. However, the current technology in radio design techniques that enables reuse hardware designed across multiple waveforms such as device modularity and software radio can easily take care of both effects.

Finally, and as a way of summarizing this section on the technical and socio-economic benefits currently deriving from DSA, the authors have provided enough evidence for changing radio spectrum management and control from its current fixed allocation policy to that dynamically allocated and controlled, so this should now be seriously considered. For instance, the benefits currently derived from TVWS that was made possible through DSA has enhanced socio-economic development of the EU through the provision of high-speed Internet access to it citizens. The TVWS has also enhanced radio spectrum availability without any national or regional re-structuring of the current international radio spectrum allocation policy. Likewise, the flexibility involved in DSA permits a dynamic spectrum market where licensed owners can lease out their unused radio spectrum to generate revenue, not only provides more income for the licensed owners, but also enhances radio spectrum availability and utilization. Furthermore, the lower entry costs provided by DSA has contributed to both product and business model lifecycles by enhancing production of more communication equipment and services as well as the promoting more job opportunities. This increase in worldwide production as well as provision of more job opportunities has positively impacted a number of nations' GDP and worldwide economic growth in general.

7. Conclusions

Wireless communication as revealed in this paper has entered an era of daily increase. The merger of communications and computing is occurring on a daily basis to provide an array of new wireless devices that are radio spectrum dependent. However, the current fixed radio spectrum management policy has been an obstacle to radio spectrum availability as a result of the imbalance it has created between spectrum scarcity and spectrum under-utilization. This imbalance has made radio spectrum management and its efficient utilization an interesting research area from technical, economic and managerial viewpoints over the last two decades. From these disciplines, observations have shown that radio spectrum access, trading and management policies are overdue for a change. With the rapid progress in the technology for DSA radio systems deploying CR systems, how technology, markets, and regulations ought to co-evolve to overcome the potential barriers to the success of DSA, requires urgent attention. From these three viewpoints, this paper assesses the current radio spectrum management policy and found it to be technologically and access fixed, inefficient and out-dated as a result of the capital intensive infrastructure involved.

With this observatory in mind we therefore propose the replacement of the current fixed radio spectrum allocation policy with a dynamic spectrum access model. We make the recommendation because the proposed radio spectrum management model will not only overcome the observed weaknesses in the current fixed radio spectrum allocation policy but will also revolutionize the way radio spectrum is being allocated and used worldwide. Furthermore, with the CR/DSA standardizations in place, it is obvious that the adoption of the proposed access and management model in this paper will not compromise the performance of existing radio systems that will continue to operate base on the current radio spectrum regulation. In addition, the opportunistic access the DSA offers will not only be a means of converting waste to wealth for licensed spectrum owner but will equally enhance radio spectrum utilization efficiency as well as enhancing radio spectrum availability for future emerging wireless services.

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