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Achieving a Better Energy-Efficient Cognitive Radio Network

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***Abstract*: Energy efficiency in cognitive radio networks has received lots of research attention lately due to the impact low energy efficiency has on the design, implementation and performance of the network. In this research, cognitive radio network as regards to energy efficiency has been analyzed. The importance of energy efficiency in cognitive radio networks and sources of unnecessary energy consumption in the network is also investigated. Ways in which higher energy efficiency in cognitive radio networks can be achieved is also addressed by employing suitable protocols, mechanisms and algorithm analyzed in the article. These measures can bring about low energy consumption amongst components in the network, improved sensing reliability and better energy efficiency which in turn enhances the overall network throughput.**

Keywords: Energy efficiency, Cognitive radio networks, Energy consumption, Energy harvesting, Wireless communication.

I. Introduction

The wireless communication sector has indeed been one of the fastest developing sector of the communications industry in recent years due to the fact that wireless applications has steadily been on the increase. As a result, various wireless applications and systems operating in unlicensed spectrum bands have gradually led to the overcrowding of the spectral bands making them scarce and unavailable. However, investigation into the spectrum scarcity problems by numerous regulatory bodies around the world, including the United States Federal Communication Commission (FCC) and the Independent Regulator and Competition Authority (OfCom) in the United Kingdom [1] [2], have reported that although the demand for spectrum will significantly increase in the near future the major problem is not the spectrum scarcity but the inefficiency in spectrum usage [3].

Therefore, to address the inefficient spectrum usage and spectrum scarcity problems, a new approach for spectrum management is required. This approach should be capable of providing wireless access to unlicensed cognitive radio users, also known as secondary users (SUs), by allowing them to opportunistically gain access to unoccupied licensed spectrum. Meanwhile simultaneously guarantying the rights of incumbent users, also known as primary users (PUs) who possesses a "*first class*" access or legacy rights across the spectrum [4][5]. This implies that a licensed spectrum band can be accessed by a secondary user only if not in use by a primary user. This new approach is referred to as Dynamic Spectrum Access (DSA) [3].

The cognitive radio technology [3] [6-8], plays an important role in ensuring the realization of this DSA paradigm. The concept of cognitive radio was first proposed by Mitola and Maguire in [6] where cognitive radio was described as software defined radio (SDR) [9] which possesses a more flexible approach to wireless communication. A cognitive radio has the ability to learn from its environment and intelligently adjust its parameters based on what has been learned. So in DSA, a cognitive radio can learn about the spectrum usage status of a band and automatically decides if the band is occupied by the primary user or not. When CRs are interconnected, they form Cognitive Radio Networks (CRNs).

The basic components of a cognitive radio network are mobile station/cognitive radio user terminals, base station/access point or fusion center and backbone/core networks. These three basic components compose three kinds of networks architectures in the CRNs [3].

The cognitive capabilities of a cognitive radio are realized in the form of a spectrum sensing (SS) technique. Spectrum sensing is performed by secondary users to determine which spectral band is available for use without creating any type of interference to the primary user. The cooperative spectrum sensing technique [10] [11][12] is the most effective type of spectrum sensing technique which allow multiple secondary users perform a local spectrum sensing independently and then makes a binary decision and sends this decision to the base station or fusion center (FC). The fusion center gathers these local sensing decisions and makes a final decision about the vacancy of the spectral band.

Since the cognitive radio is involved in a lot of functionalities to deliver a better quality of service (QoS) to its users, a lot of energy is being expended in order to perform the required task. When compared to a conventional wireless network, the cognitive radio network possesses new and extra technologies and algorithms therefore, additional energy consumption arises. In the vain of avoiding interference with a primary user, a cognitive radio will have to make a decision about which spectral bands to sense, when it should be sensed and for how long it should be sensed. The sensed spectrum information must also be sufficient enough for cognitive radio to reach accurate conclusion regarding the spectral availability. Correspondingly, spectrum sensing must be fast in order to have a brilliant knowledge of the radio environment. These various spectrum sensing requirements does not only put rigorous requirements on the design and implementation of cognitive radios but it is also seen as a main energy consumption process of a typical cognitive radio network.

So therefore, it is significantly important that energy efficiency issues in cognitive radio is successfully tackled so as to create a *greener* communication, ensure high quality of service in the network, reduce environmental impacts and also cut overall network cost from the terminals to base stations thereby making communications more affordable [13]. In literatures, a lot of researches have focused on various energy efficiency issues relating to cognitive radio networks but less attention have been given to solutions regarding this problem and applying techniques to ensure an energy-efficient cognitive radio network. In [14], the authors evaluated the secondary user's sensing time required to sense a vacant spectrum band in the network on the assumption that the primary user does not reoccupy the band during the secondary user transmission. In [15], adopting the extreme value theorem, the authors studied the spectral and energy efficiency of a cognitive radio that shares spectrum with another network. A collaborative spectrum sensing protocol was proposed in [16] so as to improve the energy efficiency of the network. This was done by reducing the number of sensing reports from the secondary users to the fusion center. In doing this, the authenticity of the availability of vacant spectral band was compromised. Also in [17], a cluster-and-forward based distributed spectrum sensing scheme was proposed to reduce secondary user energy consumption. Cluster heads are formed in the network where secondary take turns cluster heads to process spectrum sensing results from other secondary users. This technique however only deals with energy efficiency involving processing of spectrum results.

This article is aimed at studying the cognitive capabilities of cognitive radio networks and also determining ways and techniques in ensuring a more energy-efficient cognitive radio network.

In this article, a general overview of cognitive radio, its architecture and energy consumption is discussed. How the energy efficiency of a cognitive radio network limits its operation is studied and protocols to improve the energy efficiency is also discussed. The article is structured as follows. In the remainder of section 1, cognitive radio architecture is discussed. Section 2 discusses the capabilities of a cognitive radio network while section 3 explores the cognitive radio user behavior. The energy efficiency of cognitive radio networks is analyzed in section 4 and its energy consumption is investigated in section 5. Ways in which higher energy efficiency can be achieved in cognitive radio networks is investigated in section 6 and section 7 concludes the paper.

A. Cognitive Radio Architecture

A cognitive radio network (CRN) is not just a network of interconnected cognitive radios but CRN are composed of various kinds of communication systems and networks that can be viewed as a sort of heterogeneous network. Cognitive radios in a CRN, has the ability to sense available networks and communication systems around it. A typical CRN environment also consists of a primary user or a number of primary radio networks that coexist within the same geographical location of a cognitive radio network. A primary network is an existing network that is licensed to operate in a certain spectrum band. Hence, a primary network is also referred to as a licensed network. The design of cognitive radio network architecture has the objective of optimizing the entire network utilization, rather than only maximizing spectral efficiency [3].

CRNs can be deployed in centralized, distributed, ad-hoc or mesh architectures, and serve the needs of both licensed and unlicensed user applications. The basic components of CRNs are cognitive users, the primary user, base stations and core networks. These four basic components compose the three kinds of network architectures in CRNs which are infrastructure, ad-hoc and mesh architectures [18].

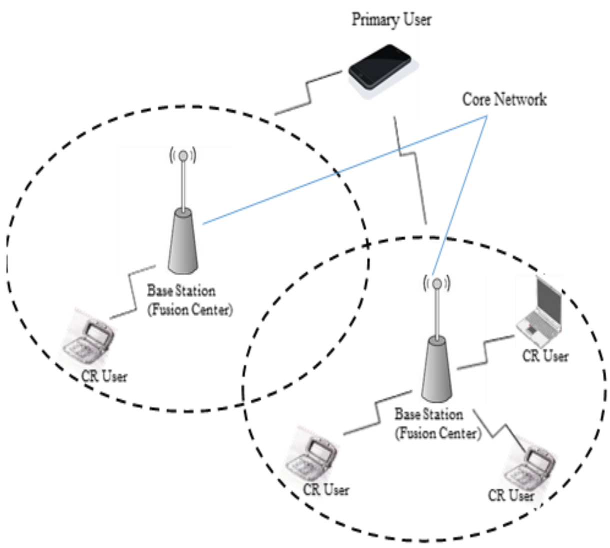


Fig. 1. Infrastructural Based Architecture

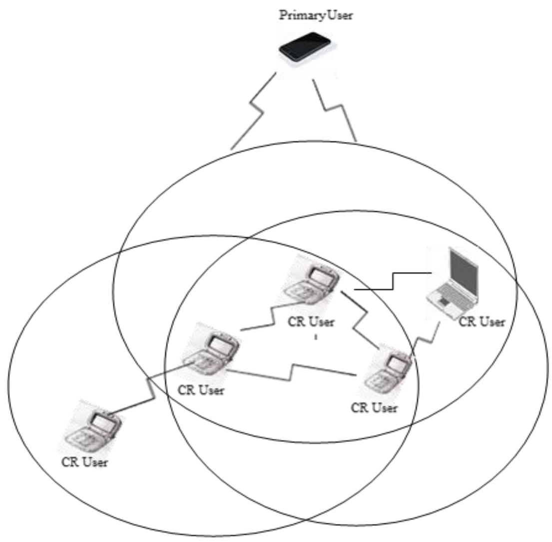


Fig. 2. Ad-Hoc Architecture

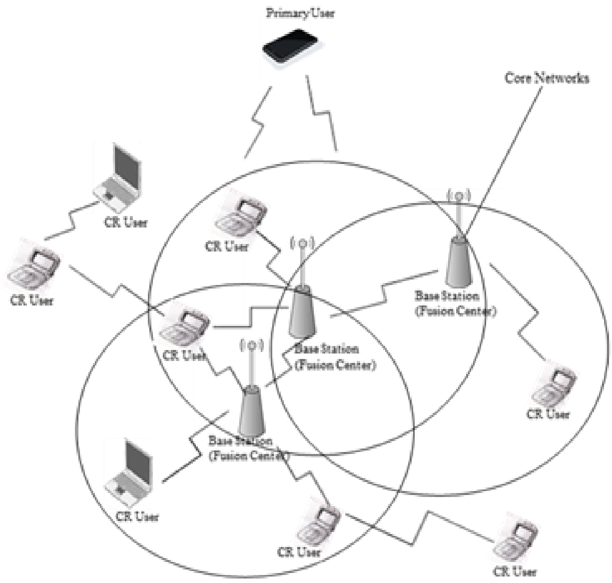


Fig. 3. Mesh Architecture

The infrastructure base architecture as shown in figure 1, operates in a manner that the cognitive radio base station controls and coordinates the transmission activities of the secondary cognitive radio users. In the ad-hoc based infrastructure as shown in figure 2, there is no infrastructural support. The CR users communicate directly with each other in an ad-hoc manner and information is shared between the cognitive radio users who fall within this communication range. While the mesh infrastructure as illustrated in figure 3 combines both the infrastructure and ad-hoc based architectures [3].

II. Capabilities of a Cognitive Radio Network

In this section, we will be exploring the capabilities of cognitive radio networks as it relates to its terminals or nodes and classify them according to their functionalities. The classification will be based on its cognitive capabilities, self-organized capabilities and reconfigurable capabilities.

A. Cognitive Capabilities

One of the very distinct capabilities of the cognitive radio is its ability to sense a spectrum for availability. It is able to detect frequency bands or spectral bands that are not being used by primary users and communicate in them as long as interference is kept at a tolerable threshold. Spectrum sharing is also another capability of a cognitive radio where spectrum can be shared between secondary users in the network with or without a need of a prior agreement. Spectrum can also be shared between a primary user and a secondary user under a term of agreement between users.

Cognitive radios also possess a location identification characteristic. That means it has the capability of determining its location and the location of other users in the network and then selects the suitable operating parameters for transmission. Cognitive radio also has the capability of discovering available networks around its location for the best communication. For example, where a cognitive radio user places a phone call, it automatically determines if there is a base station or a WiFi access point close by. If there is no direct communication between the cognitive radio user and the base station/WiFi access point but through cognitive radio users some access networks are reachable, the call can still be made in this circumstance. Cognitive radios can also discover services s around a specific location since some networks or system operators usually deliver their services via access networks.

B. Reconfigurable Capabilities

The capability of a cognitive radio being able to modify its operating frequency is also a major strength. It dynamically selects the appropriate frequency for transmission based on the signals sensed from other transmitters by employing any of the spectrum sensing methods. Cognitive radio also possesses an adaptive modulation technique which enables it to modify its transmission characteristics and waveform to provide a more intensive use of the spectrum. It can also select more suitable modulation types for its usage with specific transmission systems to enable interoperability between systems.

Power control technique is another capability of a cognitive radio which allows it to dynamically switch between different transmission power levels during data transmission. It can reduce its transmission power level to allow greater sharing of spectrum when high power transmission is not needed. It can also access multiple communication networks/systems running in different protocols by reconfiguring itself to be compatible with these networks/systems.

C. Self-Organized Capabilities

Cognitive radio networks have the capability of self-organization. It can be able to effectively organize and manage spectrum sensing information amongst cognitive radios and apply proper spectrum management techniques when required. It also possesses the capability of an accurate mobility and connection management which assist in neighborhood detection, detection of available connection access and support which enables cognitive radios to select route and networks. Lastly, Cognitive radio networks have a well-defined security or trust management, but due to its homogenous nature, security has been compromised lately by malicious users who take advantage of the network [19].

III. Cognitive Radio User Behavior

We discuss cognitive radio user behavior as it relates to energy savings since the most important stakeholder in any communication network is the user. A CR is a learning entity that autonomously senses and makes decisions based on the environment in which it operates. However, user–device interaction is usually overlooked. We discourse an example from modern cellular devices about how user–device interaction can save energy, but the arguments also apply to CR devices. Almost all up-to-date cellular devices or smartphones have several wireless interfaces: Bluetooth, WiFi, and GPS units in addition to third/fourth generation (3G/4G) cellular. Moreover, these devices have all of these circuits switched on in their factory setting. On the other hand, an average user does not frequently use these protocols, especially Bluetooth and GPS. The critical point is that the user does not care about the energy consumption of these circuits unless the device has a low battery. In addition, some users do not know how to turn them off to save energy. Thus, these protocols periodically seek some pairing or association all the time [3].

A CR device can learn and analyze user behavior such as when and/or where the user utilizes these types of additional communication units, and turn them off when it predicts that they are not needed. In addition to the end-user side, user behavior modeling can also let the operator and network designer make their short- and long-term plans with a view to increasing energy efficiency. These plans include elements such as frequency allocation, radio access network design, and operational time table for network equipment. For instance, the operator may switch the backbone equipment to low-power mode if its prediction based on the users' behavior indicates that the network traffic will be minimal for a specific location and time period [3].

IV. Energy Efficiency of Cognitive Radio Networks

Energy efficiency in cognitive radio networks has become a very serious concern to many wireless networking stakeholders due to the fast development in the world of wireless communications. Since cognitive radio networks consist of energy demanding components like its terminal nodes, base stations and backbone networks, the network lifetime is completely dependent on the energy expended by these components in the various stages of communication. So therefore, energy efficiency must be taken into consideration in every aspect of cognitive radio network operation and design.

There are several ways in which energy can be saved in cognitive radio networks. One of them is to save energy in different levels of the cognitive radio's activities while another way is to reduce interference to the barest minimum and attain a high signal noise ratio with the same transmission power. Another way is also to increase the speed of sensing so as to save energy in periodic sensing and also save time in working under active modes.

A. Importance of Energy Efficiency in Cognitive Radio Networks

As the number of wireless devices and equipment continue to increase, there will always be a corresponding increase in the demand for more energy supply and a constant pressure in crafting out more energy-efficient devices. The pressure to optimize the energy efficiency of cognitive radio networks is solely not on the operator's shoulders but on the device manufacturers who will be able to manufacture and design more compelling solutions for the operators to implement and also for the consumers to purchase. Global warming has also become an important factor not to be overlooked in recent times and most government agencies, network service providers, manufacturers of network devices and also users are now disturbed about the energy efficiency issues of wireless devices than they used to. The importance in optimizing energy efficiency in cognitive radio networks are numerous but most of them points to the issue of design, green communications policy, savings as regards to monetary cost and end user's gratification and fulfillment.

The more the energy being expended a wireless device, the more the heat due to the fact that energy used up in wireless devices gives rise to heat. When a cognitive radio user is in communication, heat is given out and if the device becomes overheated, it will start malfunctioning or might totally or partially become destroyed. To reduce the temperature, a fairly large cooling system might be needed but this cannot be applicable to mobile wireless devices. The installed cooling system will also need extra energy to run which will also give rise to more heat. As a result of this design issues, there is the need for wireless communication devices to be more energy efficient.

Environmental issues such as green-house gas problem have also been a major source of concern to various government agencies around the world. The more energy being used, the more green-house gas is being produced. Due to this reason, a lot of compulsory and non-compulsory standards now necessitate wireless devices to be more energy efficient. With these standards in place according to country regulations, manufacturers now use them to market their products since consumers are far more willing to buy products that cause lesser harm to the globe [20]. So, applying energy efficiency protocols in cognitive radio networks can reduce energy consumption and also be easily certified by these energy efficiency standards.

Currently, over 80% of the power in mobile telecommunications is consumed by radio base stations [21]. Base stations require a large amount of energy to transmit and receive wireless signals. With an efficient energy usage protocol put in place, lesser amount of heat will emanate from wireless components in base stations. If lesser amount of heat is generated, lesser energy will be required to maintain the environmental temperature of base stations. In doing this, the service provider can be able to save some cost on electricity.

Cognitive radio users in a cognitive radio network normally have a high expectation of mobility for their networking terminals. They will always prefer a lighter weight, longer battery life wireless convenient devices. On the other hand, new researches on battery technologies can expand the battery capacity. So therefore, a good energy efficiency protocol could save power and increase battery life. Better energy efficiency measures are needed by government, power agencies, service providers, manufacturers, societies as well as the cognitive radio users. In providing these, energy efficiency protocols will require various measures to make a cognitive radio device run more efficiently.

V. Energy Consumption in Cognitive Radio Networks

Currently, a lot of money is being wasted trying to lessen the energy consumption of cognitive radio networks especially in the radio base station component of the network which is seen to consume a substantial amount of energy because of its provision of radio frequency interface between network and mobile terminals. The number of base stations in a cognitive radio network is a function of how much energy will be consumed in the network. The energy consumption of a single typical base station could vary from 0.5kw up to 2.0kw [22].

There are so many other factors that negatively affect the energy consumption in cognitive radio networks but a large amount comes from its spectrum sensing process. The cognitive transceiver hardware for instance is required to attain a high sensitivity for a wide range of spectrum while accurately detecting diverse and frequency-dependent primary signals at different received power levels. This in turn makes the linearity, sensitivity and dynamic range of the circuitry of the RF front-end more demanding and also requires the antenna, power amplifiers and analog-to-digital conversion units to put in more energy [23].

A considerable amount of energy is required by a cognitive radio user to deliver secondary data via spectrum holes. Therefore, a high processing power is needed by the signal processing units to effectively evaluate the already sensed spectrum for the cognitive radio to make a decision with relatively low delay accounts for a huge portion of the total energy consumption in the network. Consequently, the energy consumed by a high power amplifier of a cognitive radio transceiver is about 70% of the total energy consumption when transmitting [24]. If the power at the cognitive radio terminal can be successfully managed, it can considerably tackle the energy consumption issues in the cognitive radio networks. There are also considerable amounts of energy consumed by cognitive radio users at different states of the cognitive radio user's activity. They are energy consumed at the transmission state, collision state, idle state, sleep state, channel scanning and back-off states [25]**.**

A. Sources of Unnecessary Energy Consumption in Cognitive Radio Networks

There exist several causes of unwanted energy consumption in cognitive radio networks either by the cognitive radio user's behavior or unwanted energy consumed by the system itself. If a transceiver is idle during low traffic period, measurements show that when applications are turned on during that period, the energy consumption when the interface is turned while in idle mode is more than the energy expended when receiving packets [26]. Also, the inactive mode of the cognitive radio which is the period immediately before a transceiver goes into or out of the standby state after an inactive period can cause the transceiver to be in a high energy consuming mode unnecessarily for a substantial amount of time.

In a wireless broadcasting environment, a cognitive radio receiver needs to be turned on during this period so as to receive broadcast messages from the radio base station bringing about a large amount of energy consumption. When a base station transmits a traffic schedules to a cognitive radio user, the user needs to receive these traffic control information recurrently in order to check for queueing downlink traffic. Also, when the user and the radio base station is not synchronized, the user can receive unwanted data before it receives the actual traffic control which gives room to unnecessary energy consumption.

Quite a lot of time, resources and energy have been spent by a cognitive radio mobile user in switching from receiving mode to transmitting mode and vice versa and also from sleep mode to transmit or receive mode. The transition from switching in between modes is usually characterized by a significant use of energy. When collision occur during transmission, the data becomes unwanted and the energy used in transmitting that data will be wasted. Another source of unnecessary energy consumption is the high error rate that occurs in the network. When data is not received properly, the energy used in transporting and processing the data is wasted. To mitigate and control the error rate issues in the network, error control protocols and mechanisms such as error correction techniques and error retransmission techniques are applied which also uses energy. Energy is further expended in the transfer of redundant data packets and error detection codes. Finally, implementing simple energy saving protocols consumes less energy than implementing complex energy saving protocols, so therefore, energy saving protocols that requires less energy to run should be employed in a cognitive radio network than the otherwise.

VI. Ways in Achieving Higher Energy Efficiency in Cognitive Radio Networks

A significant number of hurdles must be overcome in order to attain improved energy efficiency in cognitive radio networks. Since a cognitive radio network consist of several components, different protocols, mechanisms, algorithms and approaches needs to be applied in different stacks of the network. Most of these approaches are majorly concerned about the reduction of power consumed during the different modes and activities of a cognitive radio, like the active, ready or sleep state. Also, some of them are concerned about the reduction of interference in the wireless transmission rate so that the error rate and the need for retransmission can be decreased. Other measures of achieving higher energy efficiency in cognitive radio network are also concerned about increasing the transmission rate which could lead to a reduction in the total time of transmission. Collecting green energy can so be seen as a way of improving energy efficiency since it can serve as a source of power supply so that the network would not be dependent on the power supply from other sources. In this section, we will be analyzing and discussing possible measures that can lead to achieving higher energy efficiency in cognitive radio network.

A. Base Station Sleep/Inactive Mode

Switching to the sleep or inactive mode of a base station is one method of increasing the energy efficiency of a cognitive radio network. Although the radio base station sleep mode has a negative potential to bring about delay in service and worsen the QoS for cognitive radio users, but when proper protocols are applied energy consumption can be effectively minimized. When a radio base station is on sleep mode, its radio transmissions are switched off under low traffic load conditions and the power amplifier inside the radio base station is shut down. The power amplifier consumes most of the radio base station's energy and shutting it down means that the power amplifier's cooling equipment and the signal processor is also cooled down. A base station can automatically shut itself down or disable entire transmission to further reduce the power requirements if it has no or very little number of users [27]. Radio base station sleep mode can be activated in two ways, the micro sleep mode and the deep sleep mode. During the micro sleep mode, the radio base station seizes its transmission for a small period of time and are required to wake up almost immediately but in the deep sleep mode, the radio base station shuts down its transmission for an extended period of time and some of its transmit circuits are completely switched off.

The authors in [28], proposed a novel queueing system for a radio base station where the radio base station uses a virtual queueing protocol for sojourning users. As users seize using the base station, the queue goes empty and the server now is a closedown time to await new users. When new users eventually arrive during the closedown time, the server admits the new users and resumes service. But when the closedown time expires and no users arrive at the base station, the server automatically goes into sleep mode. During the sleep mode period, if users arrive into the queue, the server resumes its operation to serve the new users.

A protocol to increase the energy efficiency in a sleep mode is also seen in [29] where an algorithm was introduced in small cell base stations to toggle powers in idle conditions so that their energy consumption can be modulated. In the sleep mode, the scheme allows the base station hardware to authenticate if the subscriber requesting access to the resources is an authentic user that is registered to the network before switching itself on. A small cell base station can also be amplified with a low-power sniffer capability which allows the detection of an active call attempt from the user mobile terminal to the base station. Employing this procedure, the small cell base station can afford to disable its pilot transmissions and radio processor so as to improve the energy efficiency.

Another approach that can be implemented on the base station sleep mode is to enable the user mobile terminal decide the wake-up and sleep cycles of the base station which it is in proximity with according to its wake-up signals. When the small cell base station is in sleep mode, it still maintains the ability to receive wake-up signals from a user mobile terminal and immediately the signal is received, the small cell goes into a ready state. The user mobile terminal wake-up broadcast can have an identification information embedded in it so that the small cell base station can recognize if it is an authentic registered user communicating. This approach can be employed by enabling the user mobile terminal to always transmit a wake-up signal such that once the user mobile terminal enters into a coverage area of the radio base station, the radio base station will immediately respond to it and wake-up.

B. Multi-Antenna System

Energy efficiency in a cognitive radio network can be highly dependent on the antenna system used. A Single Input Single Output Antenna (SISO) system is easy to use and cost effective but has only one at each end of the wireless link. This is quite inferior to the Multiple Input Multiple Output antenna (MIMO) system which increases the wireless capacity of the network through additional antennas in the antenna array. The MIMO antenna system has the capabilities of increasing the energy efficiency of a cognitive radio network through its fast transmission process. With a faster transmission in the network, lesser time will be taken for the radio and its transmitter to be active and also less power will be used in transmission. Sensing of spectrum will also be faster thereby making more spectrum band available for other traffic.

Energy efficiency can be further improved in a MIMO antenna system by deactivating a certain number of antennas in certain conditions to reduce the required signals in the reduced spatial channels. The RF energy used for control signaling will reduce significantly but the operational energy used by each antenna' power amplifier will increase only if a separate amplifier is used for each radio antenna [27]. Cognitive radios with MIMO antenna system combined with adaptive transmission techniques with prior transmission channel knowledge can bring about increase in spectral efficiency as well as energy efficiency since accurate information of actual wireless channel conditions for both the transmitter and the receiver is essential. This information is transferred in the form of reference symbols or pilots which are acknowledged by the receiver [30].

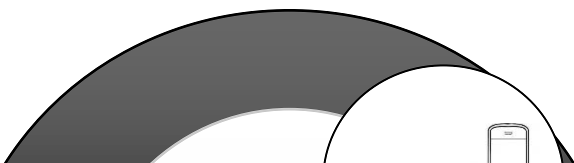
With the issue of overhead in low load situations becoming an issue for energy efficiency in MIMO antenna systems, the authors in [31] investigated the capacity of multi-element antenna systems in microcells and picocell environments. They proposed a model which they used in determining the antenna's spatial correlation in uniform broadside linear and circular array. It was shown that increased capacity has the benefit to carry more users for the same amount of resources, thus increasing the energy efficiency of the network.

C. Use of Relays

Relays can be seen as an alternative to using Multi Antenna systems in enhancing the energy efficiency of cognitive radio networks. The key purpose of a relay is to assist in forwarding information from a user in a poor signal coverage area to a radio base station. It can also be used in increasing the base station coverage area and improve the network performance where desired without necessarily affecting the radio frequency power of the base station. This approach actually goes a long way in improving the network efficiency of the network. They can also be used in decreasing the transmission power of a user's mobile terminal thereby resulting to a longer battery life.

Relays normally operate when there are users using them, in other words, relays do not unnecessarily broadcast their existence if there are no known users in their coverage area so that energy will not be wasted [32]. With the use of relays, the cognitive radio transmission power can be minimized due to decreased in distance between the transmitter and the receiver. That means that the transmission power savings highly depends on where the relays are positioned. An example of a simple positioning of a relay between the user terminal and the radio base station can be seen in figure 4. Three algorithm to optimize the relay's placement and sleep pattern so as to minimize the transmission and circuit power consumption was discussed in [33].

Modern developments in the physical layer cooperative relaying technology was discussed in [34] and [35] where the Decode-and-Forward relaying method was used to improve the wireless data rate by exploiting the spatial diversity in the physical layer. The capacity improvement gained from the



cooperative relaying is due to the exploitation of the received signals that where initially taken as noise and interference.

D. Interference Management

Interference can significantly contribute to the increase in the noise from channels in use and can also bring about the reduction in the signal-noise ratio of the transmission channel. For signals to be transmitted in channels with strong interference, an increase in the power consumption might be needed which could actually cause the signal to interfere with other signals. Cognitive radio can be able to solve this problem by practically avoiding using channels capable of causing interference. Cognitive radio might not be able to solve the possible interference issues arising from the signals the device produce which could affect other devices. In [36], the authors developed a protocol that can effectively manage interference from the device in order to avoid it interfering with other devices.

Since the 802.22 and 802.11af use the television white space, they will be needing a coexistence method in other to avoid interference among the stations that use the television white space in that location. The 802.19.1 proposal protocol was practically designed in [37] to offer solution to the coexistence problems in the television white space. The approach uses discovery to locate white space objects that has the potential of affecting the performance of others and then uses a decision technique to categorize the different white space objects and allocate channels accordingly. This can significantly increase the spectral efficiency and energy efficiency of the network.

E. Energy Harvesting

In the rural areas where power lines are not able to supply energy, energy efficiency in cognitive radio networks becomes a major problem and there will be the need for wireless devices in these areas to acquire energy for themselves. Energy sources like radio frequency energy, thermal energy, solar energy and wind energy are all potential sources of energy. These types of energies can be regarded as “green energy” and are environmental friendly.

In a battery based cognitive radio network, it is quite problematic to keep the battery life since it is quite difficult to keep supplying the device with a constant power source. Energy harvesting is very essential in its implementation on cognitive radio networks because energy can be derived from renewable source of energy thus extending the life of non-renewable batteries. Radio frequency energy is gradually becoming a desirable energy source since it can be able to convert and store energy easily. There exist several protocols that can be applied in order to efficiently harvest energy. In [38], the authors proposed an adaptive opportunistic routing protocol which can achieve an improved throughput of energy harvesting.

VII. Conclusion

Energy is considered as a major constraint in the design, implementation and performance of cognitive radio networks. In this article, we have studied the cognitive radio network architecture and various ways in which higher energy efficiency can be achieved in the network. Cognitive radio user behavior and energy consumption in cognitive radio networks were also examined. Cognitive radio is expected to deliver high Quality of Service (QoS) to its users and because of this; it possesses various functionalities and capabilities which include spectrum sensing and spectrum management, network discovery and reconfigurable abilities. These intrinsic abilities have unfortunately made the cognitive radio more energy demanding.

The energy consumption in a cognitive radio network is due to so many factors and a majority of it comes from the spectrum sensing process of the cognitive radio and the radio base stations present in the network. A considerable amount of energy is also consumed by some unnecessary operations and protocols in the network which can possibly be avoided or minimized if appropriate mechanisms are applied.

It is also seen from this article that in attaining high energy efficiency in cognitive radio networks, a significant number of hurdles needs to be overcome. In overcoming them, effective and resourceful mechanisms, algorithms and protocol need to be put in place so as to improve the energy efficiency of the network.

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